

2018

Soil carbon sequestration potential of tree windbreaks in the U.S. Great Plains

Ala Ali Khaleel
Iowa State University

Follow this and additional works at: <https://lib.dr.iastate.edu/etd>



Part of the [Agriculture Commons](#)

Recommended Citation

Khaleel, Ala Ali, "Soil carbon sequestration potential of tree windbreaks in the U.S. Great Plains" (2018). *Graduate Theses and Dissertations*. 16607.
<https://lib.dr.iastate.edu/etd/16607>

This Thesis is brought to you for free and open access by the Iowa State University Capstones, Theses and Dissertations at Iowa State University Digital Repository. It has been accepted for inclusion in Graduate Theses and Dissertations by an authorized administrator of Iowa State University Digital Repository. For more information, please contact digirep@iastate.edu.

Soil carbon sequestration potential of tree windbreaks in the U.S. Great Plains

by

Ala' Ali Khaleel

A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Sustainable Agriculture

Program of Study Committee:

John C. Tyndall, Co-major Professor

Thomas J. Sauer, Co-major Professor

Lee Burras

The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this thesis. The Graduate College will ensure this thesis is globally accessible and will not permit alterations after a degree is conferred.

Iowa State University

Ames, Iowa

2018

Copyright © Ala' Ali Khaleel, 2018. All rights reserved.

DEDICATION

"اللَّهُمَّ أَنْفَعْنَا بِمَا عَلَّمْتَنَا, وَعَلِّمْنَا مَا يَنْفَعُنَا, وَزِدْنَا عِلْمًا إِلَى عِلْمِنَا"

To my parents,

Ali Khaleel and Entesar Kamar, to whom I owe so much,

To my best half and partner,

Mohmmad Al-Qaisi, to whom I owe the most,

To the eternal love and the magnificent blessing bestowed on me, my son,

Nasser Al-Qaisi,

Without your constant love and support I would not be where I am today.

This success is dedicated to all of you.

TABLE OF CONTENTS

	Page
ACKNOWLEDGMENTS	v
ABSTRACT.....	x
CHAPTER 1. GENERAL INTRODUCTION	1
Thesis Organization	4
References	4
CHAPTER 2. CHANGES IN SOIL ORGANIC CARBON AND SOIL PROPERTIES BENEATH TREE WINDBREAK PLANTINGS IN THE U.S. GREAT PLAINS	7
Abstract.....	7
Introduction	8
Materials and Methods	11
Study area and Data Site description.....	11
Soil Sampling	12
Soil preparation and laboratory analyses.....	13
Soil analyses and calculations.....	13
Statistical analysis	15
Results and Discussion	15
Carbon and nitrogen with depth	15
Other soil properties	21
Bulk density	22
Water and KCl pH.....	22
Aggregate stability	23
Conclusion	24
Acknowledgment.....	25
References	25
Appendix Supplement Data.....	45
CHAPTER 3. CONTRIBUTION OF TREE WINDBREAKS TO DEEP SOIL ORGANIC CARBON STORAGE IN SOILS OF THE U.S. GREAT PLAINS.	67
Abstract.....	67
Introduction	68
Materials and Methods	72
Study sites.....	72
Soil sampling.....	72
Soil preparation and Laboratory Analyses	73
Calculation.....	74
Statistical analysis	75

Results	76
Soil C changes	76
$\delta^{13}\text{C}$ of SOC and plants	76
Plant sources of SOC in soil.....	78
Discussion.....	79
The changes in $\delta^{13}\text{C}$ of SOM with depth.....	79
Tree contribution to SOC with depth.	80
Conclusion	83
Acknowledgment.....	83
References	84
CHAPTER 4. CONCLUSION.....	97
References	99

ACKNOWLEDGMENTS

With my sincere gratitude, I wish to thank every person who has come into my life and helped, inspired, supported, guided, and illuminated me through their presence. I would like to acknowledge and express my deepest gratitude to the following people for their extraordinary support and contributions to this special journey and to the creation of this thesis. This work would not have been possible without them.

First and foremost, I would like to thank my major advisor, Dr. Thomas Sauer, for generously sharing his knowledge and experience throughout the course of this research. I am forever indebted to him for the magnificent guidance, patience, and support that he provided. I also would like to thank my co-major advisor, Dr. John Tyndall, for his invaluable comments and feedback that he provided throughout the entire research and writing process. Working with them has been a priceless learning experience. In addition, I am deeply appreciative for my committee member, Dr. Lee Burras, for taking the time to read my thesis and for his invaluable suggestions and recommendations to improve my work. I am forever indebted to Drs. Tom, John, and Lee for their encouragement and helpful feedback.

The next two people I would like to express my sincere gratitude to are my former professors at the University of Jordan: Dr. Luma Al-Bana and Dr. Nida'a Salem. Drs. Luma and Nida'a have helped and supported me throughout this journey. I was honored to work in their lab as an undergraduate research assistant. The knowledge and experience they provided me were extremely valuable and have had a long lasting impact on me. I would like to thank them for their personal and professional support, and for always encouraging me to keep working to achieve my ambitions.

I am also grateful to my graduate student colleagues, faculty and staff in NREM and NLAE, undergraduate employees, and friends. While it is impossible to mention all of the individuals who have contributed to this work, there are some I must call out by name. First of all, my current and former PLUS lab compatriots, especially, Emily Zimmerman and Gabrielle Roesch-McNally, for the chocolate, delicious food, and emotional support. Emily and Gabrielle have supported and helped me so much during my time at ISU. Gabrielle and, her husband, Joe, have been a great support during many tough times as well. I also would like to thank them for hosting a wonderful baby shower for my family at their cozy home. Words fail me when it comes to appreciating the efforts they took in planning and throwing a thoughtful party. Special thanks go to Emily for everything she has done and brought to me and to my family. I guess there was nothing better than starting my days off after finding her gifts, chocolate, coffee, etc. on my desk. Also, I want to express my sincere gratitude for Dr. Dick Shultz for being such a wonderful and helpful person. He has taught me so much and I will never forget our discussions. Finally, I wish to thank Kevin Jensen for all the help and support he gave along the way, he has always been nice to me.

Of course I could not have done this without my friends and family. In particular, I have first to acknowledge my partner and best-half, Mohammad Al-Qaisi, for his countless support, and whose love knows no limit. His confidence in me empowered me to successfully complete my M.S studies. I wish to thank him for all the times he cheered me up when I felt tired and frustrated, for always being there and listening to me. I think I could not have made it this far if it was not for his daily encouragement. I am grateful to have him in my life and by my side along the way, especially during the writing process.

I am very happy that I have successfully finished this work, however, my biggest joy is yet to come, and I will be beyond thrilled the day he finishes his doctorate degree and become Dr. Mohammad Al-Qaisi. No words can really describe how grateful I am to have such a wonderful partner to share this milestone and the rest of life's experiences with. To say thanks will not suffice my gratitude for him.

To my eternal love and the most precious jewel of my life, my son, Nasser Al-Qaisi, who illuminates every step I take through his very existence. Because of him, I was able to smile even after a very tough day. He has made me happier, stronger, better, and more fulfilled than I could have ever imagined. Nasser, habibi, you have grown up seeing us study and busy, but since the day you were born, your dad and I vowed that we would do everything it took to give you the best life possible. You have always been smart, strong, daring, confident, and social and we hope to see you blossom into the amazing individual you are meant to be. Nasser, I am very proud of you, I love you so much, habibi, and I wish you a very bright future.

Also, I wish to thank my friend Dr. Adriana Calderon for her sincere friendship. She was the one who helped me to acclimate to Ames. She has always supported and motivated me to start my master's degree. I am very lucky to have her in my life and I was fortunate that I got to spend a wonderful time with her in Ames. Thank you Adriana for everything you have made to us. Second, I want to thank my friend Ozlem Karakaya, her husband Kadir Karakaya, and of course their little angel Mehmet Asim for being a great support for us. They have been wonderful friends and we really enjoyed all the delicious Turkish food they have cooked for us. I look forward to many more times to spend together in Ames.

Last but not least, I would like to thank my parents, Ali Khaleel, and Entesar Kamar, for their support, for raising me to be what I am now, for their patience, care, and never-ending love, and for the many sacrifices they have made to see me successful. You both have instilled in me a love for science from a very young age. I wish to thank them for giving me many opportunities to travel and explore the world at a very young age, I never thought that this will have a very long lasting impact on me. Mom and Dad, there are no words to describe how grateful I am for both of you. Also, I wish to thank my brothers and sisters, especially, Nael Khaleel, who has supported and helped me so much during my undergraduate journey, without him, I would not get my Bachelor's degree, and I would not be what I am now. I wish to thank him for all the sacrifices he has made to help me achieve my dreams, I am forever grateful for him. Also, thanks to my sister, Wafa'a, for her believes in me, and for motivating me to keep going. In addition, I wish to thank my sister Basema and her husband for always encouraging me to work hard, and my sister Asma'a for her love and support. There was nothing better than travelling to Texas to spend some time with her and her precious family. Finally, I wish to thank my parents, brothers, and sister in-law who kept me in their prayers and cheered me up during this journey.

Thanks for the landowners for allowing us to sample and work in their farms. I also appreciate the funding from North Central Region-Sustainable Agriculture Research and Education Center. Thanks to the ISU Graduate Program in Sustainable Agriculture for the further financial support they have also provided.

I understand that this thesis is just the beginning and I look forward to learning and contributing more. I am very excited to begin my next journey.....

“Live if you were to die tomorrow. Learn as if you were to live forever.”

Mahatma Gandhi

ABSTRACT

Agroforestry practices are tree-based systems (such as tree windbreaks) strategically integrated into agricultural landscapes to variously and often simultaneously produce marketable products directly while enhancing the production of other crops, and/or provide a broad array of environmental services such as carbon sequestration. Tree windbreaks have been planted extensively in the U.S. Great Plains following a large tree planting program during the Dust Bowl of the 1930's. Windbreaks are one or multiple rows of trees and shrubs that are established for reducing wind speed. Windbreaks have been assessed for their ability to provide cellulosic bioenergy feedstock and carbon (C) sequestration opportunities. The integration of deep-rooted trees in the landscape has been assessed for enhancing carbon (C) storage and sequestration potential in biomass and in deeper soil profiles. Information on soil C storage and dynamics of trees, especially in deeper soil profile is, however, inadequate. This thesis presents a series of integrated studies to advance understanding of the impact of trees on soil organic carbon (SOC) storage and on soil physical and chemical properties. For this, the study evaluated eight tree plantings within the original Prairie States Forestry Project (PSFP) shelterbelt planting zones for representative tree species, soils, previous land use, and climate in four Northern Great Plains states North Dakota, South Dakota, Nebraska, and Kansas (ND, SD, NE, and KS, respectively). In the first study presented in Chapter 2, changes of SOC stocks and other soil properties were quantified on soil samples collected to 1.25 m beneath the tree plantings and in the adjacent farmed fields. We found that soils beneath trees had higher SOC stocks as compared to the adjacent fields. Tree plantings decreased bulk density, and enhanced soil aggregation as compared to the adjacent farmed fields. In

addition, higher SOC stocks were found in the subsurface soil beneath trees and the adjacent farmed fields as compared to the surface soil thus, demonstrating the importance of studying deep SOC especially when regional C sequestration potential is being assessed. In Chapter 3, Stable C isotope-ratios technique was used to quantify the relative SOC contribution of tree C to the total SOC stocks. More tree-origin C was found in tree soils and at deeper depths indicated that tree presence promoted storage of C. Overall, trees show significant potential for the sequestration of SOC compared with the adjacent farmed-fields.

CHAPTER 1. GENERAL INTRODUCTION

The United States climate change assessments concluded that the U.S. climate is changing and it will continue to change during the 21st century (Wuebbles et al., 2017). The variability of temperatures and precipitations patterns is expected to become greater and to vary greatly across regions thus, posing distinct challenges on agricultural regions (Dosskey et al., 2017). Current land use in the Great Plains states of the north central region (NCR) is strongly influenced by an east-west gradient in precipitation and a north-south gradient in temperature. Drought, wind erosion and dust problems are likely to increase under climate change and cause considerable stress to the region (Dosskey et al., 2017). Historically, when similar conditions presented during the Dust Bowl era of the 1930s, the U.S. Government promoted agroforestry to address these environmental problems. Yet since that time, due in part to rising land values, lack of markets for tree-based products, and changes in agricultural technology, many of these original plantings have been removed or left unmanaged and are biophysically in decline (Schaefer et al., 1987).

An opportunity for expanded tree planting and/or increase tree management came with Energy Independence and Security Act (EISA) of 2007 which established a Renewable Fuel Standard (RFS; now updated to RFS II) mandating 36 billion gallons of biofuels be produced annually in the U.S. by 2022. Of this amount, 44.4% of the RFS is to be based on cellulosic feed stocks, such as crop residues, dedicated herbaceous crops, and woody biomass from natural and planted systems. Since this time, many states have also expanded the utilization of renewable energy including biomass based heat and electricity via legislated Renewable Portfolio Standards or less formalized renewable energy goals (Durkay, 2017). A land use system that has the potential to serve multiple purposes in the context of climate

resiliency and bioenergy production is agroforestry, a managed, productive, and sustainable land- use practice where herbaceous and woody species [i.e. trees/shrubs] are deliberately combined with agricultural systems on the same land to enhance crop productivity and ecosystem functionary (Schoeneberger, 2009). A distinct advantage of Agroforestry systems (AFS) is that the purposeful combination of trees with agricultural systems has greater potential to produce food, fiber, and forage than any one treeless system individually (Sauer and Hernandez-Ramirez, 2011). Trees exploit resources (nutrients, water, and light) through their extensive multi-layered aboveground canopies, deep extensive rooting systems, and longer growing seasons that may not captured by annual crops (Sauer and Hernandez-Ramirez, 2011) thus, AFS have great potential to increase per unit land areas productivity. Other benefits of AFS also include the capacity to sequester carbon (C) in soils and in their biomass, thus, the ability to restore degraded soils, enhanced ecosystem services, and the ability to provide cellulosic bioenergy feedstock (Schroeder, 1994; Rosenberg and Smith, 2009; Schoeneberger, 2009; Sauer and Hernandez-Ramirez, 2011). The attractiveness of using agroforestry to enhance C sequestration in soils compared with treeless systems rests on the premise that tree component of AFS can act as a significant sink for atmospheric C due to their long term storage of C in their above- and belowground biomass (Jose, 2009), especially in the deep extensive rooting system (Haile et al., 2008).

The Northern Great Plains (NGP) states have an extended history of agroforestry plantings beginning with the Prairie States Forestry Project (PSFP) of the 1930's when over 210 million trees were planted as windbreaks on approximately 237,000 acres in North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, and Texas (Droze, 1977). Windbreaks or shelterbelts designed specifically for controlling wind speed and erosion thus, protecting

soils, crops and livestock, and enhancing local microclimate (Brandle et al., 2004; Garrett, 2009). Tree-based ecosystem benefits continue to be broadly recognized by NGP landowners as important to their farming systems (Hand et al., 2017).

Few studies have examined the consequences of integration of windbreak plantings on soil organic carbon storage. Studies on the variability of soil C under different land-use systems is important for understanding and assessing the impact that tree based biomass systems may have on SOC and the associated improvement of the ecosystem benefits (Dhillon & Van Rees, 2017; Garrett, 2009; Jose & Bardhan, 2012; Lorenz & Lal, 2014; Udawatta et al., 2015). However, quantitative information about belowground C inputs in agroforestry systems is inadequate (Cardinael et al., 2015; Lorenz & Lal, 2014) especially in temperate regions (Nair et al., 2010). Moreover, most agroforestry studies considered SOC at the surface to 30 cm depth (Nair, 2012). In order to determine the full capacity of practices such as windbreaks to sequester C, it is important to study SOC deeper in the soil profile (Nair, 2012). Considering these gaps, the general objective of this thesis seeks to advance understanding of the impact of trees on soil carbon sequestration in the U.S. NGP. The specific objective are:

- Quantify the total SOC stocks to 1.25 m soil depth for eight historical tree windbreak plantings and their adjacent farmed fields.
- Determine the relative contribution of trees and the adjacent farmed fields to SOC using the natural carbon isotopic differences between C₄ (mainly warm season grasses *Zea Mays* in this study) and C₃ plants (trees and some cool season grasses).

Thesis Organization

This thesis consists of four chapters, and presented in systematic studies. Chapter 1 (this chapter) provides a brief background on the tree windbreaks history and their role in a low rainfall area like the U.S. Great Plains. This chapter also summarizes how these historical tree plantations provided an array of environmental services (e.g. soil carbon sequestration and the associated soil health benefits). Chapter 2 quantifies the impact and the potential of tree plantings on enhancing SOC storage as compared to the adjacent farmed fields which included forage production and cropped fields. Using the natural abundance of stable C isotope-ratio (^{13}C), the source of SOC was traced into its origins (from C_3 or C_4 plants) (Chapter 3). Chapter 4 summarizes key finding of this research and provide general conclusions. In addition, chapter 4 provides suggestions for future research needs. Chapter 2 and 3 are manuscripts which will be submitted for publication.

References

- Brandle, J. R., Hodges, L., & Zhou, X. H. (2004). Windbreaks in North American Agricultural Systems Windbreaks in North American Agricultural Systems. *Agroforestry Systems*, 61(Burke 1998), 65–78.
- Cardinael, R., Chevallier, T., Barthès, B. G., Saby, N. P. A., Parent, T., Dupraz, C., ... Chenu, C. (2015). Impact of alley cropping agroforestry on stocks, forms and spatial distribution of soil organic carbon - A case study in a Mediterranean context. *Geoderma*, 259–260, 288–299. <https://doi.org/10.1016/j.geoderma.2015.06.015>
- Dhillon, G. S., & Van Rees, K. C. J. (2017). Soil organic carbon sequestration by shelterbelt agroforestry systems in Saskatchewan. *Canadian Journal of Soil Science*, 97(3), 394–409. <https://doi.org/10.1139/cjss-2016-0094>
- Dosskey, M. G., Brandle, J., Bentrup, G., Bell, C. A. C., Brantly, S., Chambers, A., ... Zamora, D. (2017). *Chapter 2: Reducing threats and enhancing resiliency. In: Schoeneberger, Michele M.; Bentrup, Gary; Patel-Weynand, Toral, eds. 2017.*

Agroforestry: Enhancing resiliency in U.S. agricultural landscapes under changing conditions. Gen. Tech. Report WO-96. Was.

Droze. (1977). *trees, prairies, and people – a history of tree planting in the Plains States. Texas Woman's University, Denton.*

Durkay. (2017). State Renewable Portfolio Standards and Goals. Retrieved from <http://www.ncsl.org/research/energy/renewable-portfolio-standards.aspx>

Garrett. (2009). *North American Agroforestry : An Integrated Science and Practice* Madison, WI: American Society of Agronomy. 400 p. *The Development of Agroforestry as an Integrated Land Use Management Strategy.*

Haile, S. G., Nair, P. K. R., & Nair, V. D. (2008). Carbon Storage of Different Soil-Size Fractions in Florida Silvopastoral Systems. *Journal of Environment Quality*, 37(5), 1789. <https://doi.org/10.2134/jeq2007.0509>

Hand, A. M., Bowman, T., & Tyndall, J. C. (2017). Influences on farmer and rancher interest in supplying woody biomass for energy in the US Northern Great Plains. *Agroforestry Systems*, 1–14. <https://doi.org/10.1007/s10457-017-0170-x>

Jose, S. (2009). Agroforestry for ecosystem services and environmental benefits: An overview. *Agroforestry Systems*, 76(1), 1–10. <https://doi.org/10.1007/s10457-009-9229-7>

Jose, S., & Bardhan, S. (2012). Agroforestry for biomass production and carbon sequestration: An overview. *Agroforestry Systems*, 86(2), 105–111. <https://doi.org/10.1007/s10457-012-9573-x>

Lorenz, K., & Lal, R. (2014). Soil organic carbon sequestration in agroforestry systems. A review. *Agronomy for Sustainable Development*, 34(2), 443–454. <https://doi.org/10.1007/s13593-014-0212-y>

Nair, P. K. R. (2012). Carbon sequestration studies in agroforestry systems: A reality-check. *Agroforestry Systems*, 86(2), 243–253. <https://doi.org/10.1007/s10457-011-9434-z>

- Nair, P. K. R., Nair, V. D., Kumar, B., & Showalter, J. M. (2010). Carbon sequestration in agroforestry systems. *Advances in Agronomy*, 108(C), 237–307. [https://doi.org/10.1016/S0065-2113\(10\)08005-3](https://doi.org/10.1016/S0065-2113(10)08005-3)
- Rosenberg, N. J., & Smith, S. J. (2009). A sustainable biomass industry for the North American Great Plains. *Current Opinion in Environmental Sustainability*, 1(2), 121–132. <https://doi.org/10.1016/j.cosust.2009.09.003>
- Sauer, T. J., Hernandez-Ramirez, G., Hatfield, J. L., & Sauer, T. J. (2011). Agroforestry, 3120, 351–370. <https://doi.org/10.2136/2011.soilmanagement.c23>
- Schaefer, B. P. R., Dronen, S., & Erickson, D. (1987). Schaefer, P. R., Dronen, S., & Erickson, D. (1987). Windbreaks: a Plains legacy in decline. *Journal of Soil and Water Conservation*, 42(4), 237-238.
- Schoeneberger, M. M. (2009). Agroforestry: Working trees for sequestering carbon on agricultural lands. *Agroforestry Systems*, 75(1), 27–37. <https://doi.org/10.1007/s10457-008-9123-8>
- Schroeder, P. (1994). Carbon storage benefits of agroforestry systems. *Agroforestry Systems*, 27(1), 89–97. <https://doi.org/10.1007/BF00704837>
- Udawatta, R. P., Adhikari, P., Anoma Senaviratne, G. M. M. M., & Garrett, H. E. (2015). Variability of soil carbon in row crop watersheds with agroforestry buffers. *Agroforestry Systems*, 89(1), 37–47. <https://doi.org/10.1007/s10457-014-9740-3>
- Wuebbles, D. J., Fahey, D. W., Hibbard, K. A., Deangelo, B., Doherty, S., Hayhoe, K., ... Weaver, C. P. (2017). Climate Science Special Report. *Executive Summary of the Climate Science Special Report: Fourth National Climate Assessment, I*, 26.

CHAPTER 2. CHANGES IN SOIL ORGANIC CARBON AND SOIL PROPERTIES BENEATH TREE WINDBREAK PLANTINGS IN THE U.S. GREAT PLAINS

Modified from a manuscript to be submitted to the Agroforestry Systems

A. A. Khaleel¹, T. J. Sauer², and J. C. Tyndall¹

Abstract

Agroforestry systems (AFS) such as tree windbreaks for wind erosion control and crop microclimate modification became a common practice in the U.S. Great Plains following a large tree planting program during the Dust Bowl of the 1930's. Tree windbreaks offer opportunities to sequester soil organic carbon (SOC) and to improve the quality of degraded soils. However, our understanding of the effect of trees on SOC is largely limited to the upper 30 cm of the mineral soil. The objective of this study was to quantify the changes in SOC and relevant soil properties beneath tree plantings for representative tree species, soil type, previous land use, and climate in four Great Plains states, North Dakota, South Dakota, Nebraska, and Kansas (ND, SD, NE, and KS, respectively). Samples were collected from a soil pit and two adjacent auger holes at 0-10, 10-20, 20-30, 30-50, 50-75, 75-100, and 100-1.25 m depth increments within the trees and in a neighboring field within the same soil map unit. Soil samples were analyzed for SOC, inorganic carbon (SIC), total nitrogen (TN), pH (in water and KCl), particle size, bulk density, and water stable aggregates. Soils beneath trees averaged $2.93 \pm 2.07 \text{ kg m}^{-2}$ (mean \pm standard error) greater SOC stocks measured to 1.25 m than the adjacent farmed fields. Differences ranged from $+10.54 \text{ kg m}^{-2}$ to a -5.05 kg m^{-2} . The subsurface soil had greater SOC stocks than the surface soil beneath trees (9.54 vs. 8.84

¹ Department of Natural Resource Ecology and Management, Iowa State University, Ames, IA, 50011

² USDA-ARS, National Laboratory for Agriculture and Environment, Ames, IA, 50011

kg m⁻²) and the adjacent farmed fields (7.85 vs 7.61 kg m⁻²), respectively. This finding demonstrates the importance of studying the C stored at deeper depths under tree-based practices when the SOC sequestration potential of trees is being assessed. Overall, the results indicate the potential of trees to store carbon in soils of the U.S. Great Plains and in deeper soil depths.

Keywords agroforestry systems, deep soil organic carbon, soil carbon sequestration, Northern Great Plains.

Introduction

With the passing of the Energy Independence and Security Act (EISA) in 2007, the Renewable Fuel Standard (RFS; now updated to RFS II) mandated 36 billion gallons of biofuels be produced annually in the U.S. by 2022. Of this amount, 44.4% of the RFS is to be based on cellulosic feedstock. Since this time, many states have also expanded the utilization of renewable energy including biomass based heat and electricity via legislated Renewable Portfolio Standards or less formalized renewable energy goals (Durkay 2017). As such, throughout the agricultural regions of the United States there has been strong interest in exploring the potential of regionally based biomass systems including a mix of crop residues, dedicated herbaceous crops, and or woody biomass systems (Langholtz et al. 2016). One such region with significant biomass potential is the Northern Great Plains (NGP) region of the United States (Langholtz et al. 2016). While crop residues and herbaceous biomass systems have received a significant amount of research attention in the NGP region (e.g., McGuire and Rupp 2013; Qingwu Xue 2013; Mitchell et al. 2016) there is interest in exploring the niche potential of woody biomass in general (Rosenberg 2007; Rosenberg and Smith 2009; USDOE 2011). This interest is driven largely because of inherent advantages

that woody biomass systems have over other biomass feedstock systems with regard to energy potential, feedstock storage and logistics, and concomitant enhancement of field and watershed level ecosystem services (Tyndall et al. 2011). More recently, NGP agricultural landowners (farmers and ranchers) have expressed interest in woody biomass systems that are integrated into agroforestry practices put into place for various conservation benefits such as habitat, soil health, and carbon (C) sequestration (Hand et al. 2017).

Agroforestry practices are tree-based systems such as windbreaks, forest buffers, and silvopastoral systems, strategically integrated into agricultural landscapes to variously (and often simultaneously) produce marketable products directly, enhance the production of other crops, and/or provide a broad array of environmental services (Garrett 2009). Specific to biomass production, agroforestry systems have been assessed globally for their marketable yields and concomitant environmental services such as carbon sequestration (Montagnini and Nair 2004; Gruenewald et al. 2007; Jose and Bardhan 2012).

The NGP states have an extended history of agroforestry plantings beginning with the Prairie States Forestry Project (PSFP) of the 1930's when over 210 million trees were planted as windbreaks and buffers on approximately 960 km^{-2} in North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, and Texas (U.S. Forest Service. 1935; Droze 1977) see (Fig. 2.1). These historical plantings served a very specific purpose to help stabilize soil, conserve moisture, and protect crops, livestock, and homesteads during the unprecedented Dust Bowl conditions of the 1930's. Tree-based ecosystem benefits continue to be broadly recognized by NGP landowners as important to their farming systems (Hand et al. 2017). One critical ecosystem benefit relative to woody biomass-based agroforestry systems is C storage and sequestration; C management has both distinct ecosystem service market potential (Miller et

al. 2012) and ties into state and Federal energy goals regarding incremental reductions in greenhouse gas emissions (Cuellar and Herzog 2015).

Agroforestry systems have long been assessed for their capacity to sequester C in their biomass and for their ability to provide cellulosic bioenergy feedstock (Schroeder 1994; Rosenberg and Smith 2009; Schoeneberger 2009). Agroforestry offers great potential to improve soil quality of degraded or marginal lands by reducing soil disturbance and providing perennial ground cover (Schoenholtz et al. 2000; Boussougou et al. 2010). The potential to increase and recycle soil organic matter content (SOM) is a critical soil quality feature associated with enhanced nutrients uptake and cycling, optimal soil structure, and improved water infiltration and soil water storage and holding capacity (Hudson 1994; Teepe et al. 2003). Sauer et al. (2012) found agricultural land planted to trees had $30.0 \pm 5.1\%$ (mean \pm standard error) more soil organic carbon (SOC) than the adjacent tilled cropland in Iowa. In another Midwestern U.S. study, an estimated SOC accumulation rate of $0.11 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ was found for the surface 15 cm beneath a 35 yr-old eastern red cedar- Scotch pine windbreak in eastern Nebraska (Sauer et al. 2007). Hernandez-Ramirez et al. (2011) used stable carbon isotope techniques on soil samples from the Nebraska site and one site of the Iowa study and found 53.9 and 47.1% of the SOC in the surface layers was tree-derived with mean residence times of ~ 50 yrs. These studies concluded that the observed increase in SOC beneath the planted trees was largely associated with C from the trees.

Knowledge on the variability of soil C under different land-use conditions is important for understanding the impact that agroforestry based biomass systems may have in enhancing myriad of ecosystem benefits (Jose and Bardhan 2012; Lorenz and Lal 2014; Udawatta et al. 2015; Dhillon and Van Rees 2017). Nevertheless, quantitative information

about belowground C inputs in agroforestry systems continues to be limited (Lorenz and Lal 2014; Cardinael et al. 2015) especially in temperate regions (Nair et al. 2010). Moreover, most SOC storage studies of agroforestry systems have been limited to the surface 30 cm soil depth (Nair 2012). In order to determine the full capacity of practices such as windbreaks to sequester C, it is important to study SOC deeper in the soil profile (Nair 2012).

Given the paucity of such data especially under agroforestry systems, for this study we explore the impact that the historical tree plantings in the NGP region have had on SOC storage at depth and their potential to improve overall soil quality on soils in low rainfall areas like the NGP. The objective of this study was to quantify the changes in SOC stocks to a depth of 1.25 m at eight representative historical tree plantings with adjacent farmed fields which included cultivated fields, alfalfa, grasslands, hay and pasture under different soil and climate conditions in the U.S. NGP. We also assessed soil samples to quantify the changes in other soil properties (e.g., bulk density, aggregate stability, pH (water and KCl) beneath tree plantings and relative to the adjacent farmed fields.

Materials and Methods

Study area and Data Site description

We chose to explore soil C changes at sites within the original Prairie States Forestry Project (PSFP) windbreak planting zones. Site selection was intended to obtain representative soils, tree plantings, and cropping practices throughout the area. As such, we identified eight, tree windbreak sites for soil sampling. Two sites were selected in each state, North Dakota, South Dakota, Nebraska, and Kansas (ND, SD, NE, and KS). These sites provided a range of climate, soil type, tree species, tree age, and cropping practices in the adjacent fields. Soil samples were collected (see Fig. 2.1), and soil profile descriptions were prepared for tree

plantings and agricultural fields at each site (see Appendix. Table S2). The detailed climatic and edaphic characteristics of the study sites are presented in Table 2.1.

In general, at the McLeod site (ND), the adjacent field cultivated began in ~1880 and converted to pasture after 1935. Moreover, at the Milnor site (ND), the adjacent small grain field cultivation began in the 1880's and continued until ~1995 when it was cultivated to a corn and soybean rotation. At the Mead site (NE), the adjacent field had been under a crop rotation of corn-soybean-wheat for over 100 years. The farmed field at Stromsburg site (NE) was first cultivated back in the 1890's and had mostly been in a wheat-soybean-corn rotation. Before sampling collection, the field was planted to alfalfa for almost 10 yrs.

The Marquette (KS) site the field was under cropping management before being simultaneously planted to trees and grassland during the same year. Similarly, the Corsica East (SD) site was a single field before being simultaneously planted to honey locust trees or hay production during the same year. At the McPherson site (KS), trees were planted into native prairie, thus the soil has never been cultivated. The adjacent row crop field has been converted to no till management three years before sampling.

Soil Sampling

At each site, a soil pit to a depth of ~1.25 m was dug by hand or with a backhoe inside the tree planting and in the adjacent farmed area, which included cultivated fields, alfalfa, grasslands, hay and pasture, hereafter, we refer to the adjacent farmed area as “farmed fields”. To enhance our sampling, we also took samples from two hand auger holes adjacent to each pit at each location. Soil samples were collected after removing the surface litter or crop residue at 0-10, 10-20, 20-30, 30-50, 50-75, 75-100, and 100-125 cm depth increments within the trees and in the neighboring farmed fields within the same soil map

unit for each soil pits and auger holes. Soil pit samples were collected from three walls of the soil pit and composited by depth. In addition, soil profile descriptions were prepared by local Natural Resources Conservation Service soil scientists for trees and neighboring farmed fields pits at each site (see Appendix. Table S2).

Soil preparation and laboratory analyses

Soil analyses and calculations

Bulk density was measured following the core method (Soil Survey Laboratory Staff, 1996), core volume 256.35 cm³ (8 cm in diameter and 5.1 cm height), using undisturbed soil samples taken at 10, 30, 75, and 100 cm from each of the three pit walls. Cores were weighed, dried at 105°C for 48 hr and weighed again to determine the oven dry mass.

The field-moist soil samples were passed through an 8-mm sieve, all visible plant material removed, and a ~200 g subsample passed through a 2-mm sieve. All soil samples were then air-dried. A ~ 20 g sample of the air dry < 2-mm-diameter soil was placed on a roller mill (Bailey Mfg., Inc.³, Norwalk, IA) for 12 hr to create fine powder for total carbon (TC) and total nitrogen (TN) analyses. TC and TN were measured for all soil samples using dry combustion (Flash 1112, Thermo Finnigan, San Jose, CA). An effervescence test was used to determine if any inorganic C was present and, when carbonates were found, soil inorganic C content (SIC) analysis was completed using the pressure calcimeter method as described by Sherrod et al. (2002). To determine SOC values, SIC values were subtracted from the TC values.

³ Trade names or the commercial products in this article are solely for the purpose of providing specific information and does not imply recommendation or endorsement by authors or their institutions.

The SOC stocks (kg m^{-2}) were calculated for each soil sample and separate depth increment (Eq.1) and then added to obtain cumulative SOC stocks for the 0-30, 30-125, and 0-125 cm soil depths, hereafter we refer to it as “surface soil”, “subsurface soil” and “entire soil profile”, respectively. The change in SOC in soils beneath the trees was estimated by subtracting the SOC stocks of the adjacent farmed fields from the SOC stocks of the trees. This estimation was based on the assumption that the SOC under the trees was the same as in the adjacent farmed fields when the trees were planted.

$$\text{SOC stocks} = \text{SOC concentration} \times \text{BD} \times \text{Soil layer thickness} \quad [1]$$

Where,

SOC stocks = C stocks expressed in kg m^{-2}

SOC concentration = C in each soil layer, g per kg of soil of that depth

BD = Bulk density, g cm^{-3}

Samples of the air dry 2mm – sieved soil were used to determine pH in water (1:1 paste, Thomas 1996), pH in potassium chloride (0.01M KCl) (Moore and Loeppert 1987), and particle size analysis (PSA) (pipet method, Gee and Or 2002). Soil aggregates stability was determined by wet sieving to obtain the distribution of water stable macroaggregates (WSA) using samples of air dry 8mm-sieved soil as outlined by Márquez et al. (2004). Briefly, to fractionate aggregates, a 100 g of 8mm air-dried soil was cyclically submerged in water for 5 min using a series of 5 sieves (4, 2, 1, 0.5, and 0.25mm). The WSA retained on each sieve were oven dried at 70°C , weighed and later used to calculate the amount of WSA for each size fraction $> 0.25\text{mm}$.

Statistical analysis

A two-sample t-test at P values = 0.05, 0.01, and 0.001 was used at each site to examine the effects of land-use (trees vs adjacent farmed fields) on SOC concentration and stocks, and other soil parameters (e.g. SIC, C:N ratio, and pH). Then we examined the differences of soil parameters in the profile as follows; we tested the differences in the surface (0-30cm), subsurface (30-125 cm), and in the total soil profile (0-125cm). All statistical analyses were performed using R software version 3.4.2 (R Development Core Team, 2013).

Results and Discussion

Carbon and nitrogen with depth

Differences were observed between the soil under trees and soil from the adjacent farmed fields for all parameters over all depth increments but were not always consistent. The greatest absolute differences were in the 0-75 cm soil layers at all sites, below 75 cm less differences were observed (Table 2.2). In the surface 30 cm, SOC concentration was $24.48 \pm 12.31\%$ (mean \pm standard error) greater under trees than the adjacent farmed fields, however, the majority of this C was mainly located in the surface 0-10 cm layer of soil and was $30.32 \pm 17.48\%$ (mean \pm standard error) greater under trees than the adjacent farmed fields.

SOC concentration was always higher at the surface and declined with depth (see; Appendix, Table S1). The differences in SOC concentration [between trees and adjacent farmed fields] ranged from +15.99 to -4.31 and +5.11 to -4.96 g kg⁻¹ for surface and subsurface soils, respectively. Some of the variation in SOC can be attributed to including but not limited to; site history and management, tree age and species.

Soil beneath trees had on average $1.95 \pm 1.28 \text{ g kg}^{-1}$ (mean \pm standard error) higher SOC concentration than the adjacent farmed fields in the entire soil profile. However, soil beneath the adjacent farmed field (hay, continuous for 15 years) at the Corsica East site had significantly higher SOC concentration ($p < 0.05$) than beneath a 15 yr-old honey locust tree planting (Table 2.2, Fig. 2.2). In addition, at the Marquette site, the differences in SOC between the 29-year-old black locust trees and the reconstructed grasslands of the same age were very similar in absolute terms and not significantly different. Young trees do not have significant biomass in their early years to restore or increase SOC (Sauer et al. 2007). Moreover, at the Corsica East site, it is possible that soil disturbance during tree planting is responsible for some reduction in SOC, as has been noted in other similar situations (Paul et al. 2002; Sauer et al. 2007). Relatively low rainfall at Corsica may also result in slower tree growth that produced fewer roots and less litterfall for decomposition into SOC. Moreover, In a global review of root distribution, Jackson et al. (1996) reported that 83% of temperate grasslands roots occur in the top 30 cm, thus may be contributed to the significantly higher SOC in soils of the adjacent farmed fields.

The surface soil beneath the green ash windbreak in Mead had 19.5% greater SOC concentration when compared to the adjacent row crop field (21.85 vs. 18.27 %, $p = 0.03$), by contrast, the Mead site showed significantly lower SOC concentration beneath the trees in the subsurface soil (Fig. 2.2). Sampling site selection is a possible explanation for this variation in soil C. Although a similar sampling approach was followed at all locations, at the Mead site, the soil profile description of the tree and crop pits showed that the soils were two different series even though the crop pit was only 20 m from the tree windbreak. Thus,

spatial variation in soil properties may have contributed to anomalous results at this location unrelated to land use.

The SOC was greater under trees when expressed on an areal mass (kg m^{-2}) than for the adjacent farmed fields. However, the differences in SOC stocks in the entire soil profile (19%) were less pronounced compared to those of SOC concentration (22%). This can be attributed to the lower bulk densities under the trees as compared to the adjacent farmed fields (Fig. 2.3), which demonstrates the importance of bulk density measurements in SOC stocks calculation (Sauer et al. 2007; Dhillon and Van Rees 2017). Soils beneath trees had on average $0.67 \pm 0.51 \text{ kg m}^{-2}$, $0.25 \pm 0.17 \text{ kg m}^{-2}$, and $0.32 \pm 0.21 \text{ kg m}^{-2}$ (mean \pm standard error) greater SOC for the 0-10, 10-20, and 20-30 cm layers, respectively, as compared to the adjacent farmed fields. Overall, the subsurface soil under trees had greater SOC content than the surface soil at nearly all sites (1.69 vs. 1.24 kg C m^{-2}), respectively.

The surface soil beneath trees and the adjacent farmed fields contained only $8.84 \pm 1.10 \text{ kg C m}^{-2}$ or [48%] and $7.61 \pm 0.80 \text{ kg C m}^{-2}$ or [49%] of the total C stocks stored in the entire soil profile, respectively. Whereas, the subsurface soil beneath trees and the adjacent farmed fields contained $9.54 \pm 1.45 \text{ kg C m}^{-2}$ or [52%] and $7.85 \pm 1.05 \text{ kg C m}^{-2}$ or [51%] of the total C stocks stored in the entire soil profile, respectively. This finding is perhaps not surprising, giving several recent studies suggesting that deep SOC is a significant contributor to the C pool (Harper and Tibbett 2013; Cardinael et al. 2015). For instance, results from Harper and Tibbett (2013) examining pine reforestation in crop fields, showed that total SOC was 2-4 times greater when sampling to 5 m compared to sampling to 0.3 m. Similarly, Cardinael et al. (2015), examining alley cropping systems, indicated that SOC stocks in the surface 30 cm soil layer beneath trees contained only 16% of the total SOC stocks stored to 2

m soil depths, demonstrating the importance of subsurface soil layers for contributing to accurate C stock inventories (Harper and Tibbett 2013). This increase in SOC stocks under trees at deeper depths might be attributed to bulk density variation and to the decomposition of trees fine roots. Trees have extensive fine root system that can penetrate deep into the mineral soil (Lorenz and Lal 2014). The annual root-derived C inputs are a critical source of stable SOC in these deeper soil layers and may equal or exceed the aboveground C inputs from leaves and litterfall (Jackson et al. 1997). Therefore, the subsurface soil layers play a prominent role in increasing SOC stocks and their residence time thus, quantification of SOC at deeper depths must be taken into account to determine the full potential of tree windbreaks for C sequestration, and is necessary when C estimates of terrestrial ecosystems is being discussed (Harper and Tibbett 2013).

Over the entire 1.25 m soil profile, soils beneath trees across all sites, averaged $2.93 \pm 2.07 \text{ kg m}^{-2}$ (mean \pm standard error) greater SOC stocks than adjacent farmed fields. The differences [between tree and farmed fields] in SOC stocks to 1.25 m ranged from $+10.54 \text{ kg m}^{-2}$ for a 50+ year-old elm windbreak in Milnor to -5.05 kg m^{-2} for a ~ 40 yr-old green ash planting in Mead. Some sites offer special perspectives on tree planting effects perhaps due largely to land management history. For example, the McPherson site is unique as the trees were planted into virgin prairie, thus the soil has never been cultivated. Data from this site showed that soils beneath the ~90 yr-old Osage orange trees had higher SOC in all depth increments as compared to the adjacent farmed field (row crop field). At the McPherson site, the SOC concentration was 90% greater under the trees than in the adjacent row crop field (22.97% vs. 12.03%, $p = 0.013$) in the surface soil. The dramatic significant difference in SOC

may be attributed to the loss of soil organic matter during over a century of small grain and row crop production (Table 2.2, Fig. 2.2, 2.3).

At the Corsica West site, SOC beneath a 25 yr-old green ash tree was significantly lower than the adjacent farmed field (pasture) in the surface soil, but higher in the subsurface soil. At this site, site management such as cultivation between tree rows for weed control during the first several years after tree planting may have resulted in redistribution of organic matter rich top soil (i.e. mounding in tree rows), which complicated the soil sampling procedure and may have contributed to the highly significant difference in SOC between the trees and the adjacent pasture. However, removing Corsica West and Mead sites from the data due to their possible anomalous features would result in the SOC stocks for the entire soil profile beneath trees to increase to 22% (2.94 vs. 3.59 kg m⁻²) as compared to the adjacent farmed fields.

Soil inorganic carbon (SIC) was only found at the Corsica East and West, McPherson, and Milnor sites and only at deeper depths except at Corsica East where the depth of carbonates was at 20-30 cm under the trees and in the farmed field. No significant differences were found at the mentioned sites with the exception of the Corsica west site where the adjacent farmed field subsurface soil had significantly higher SIC than under the trees.

The total nitrogen (TN) trend followed very closely with those for SOC concentration and mass with again a smaller difference when expressed on a mass per area basis due to bulk density variations (Fig. 2.4). The average differences in profile TN stocks between trees and farmed fields soils ranged from +0.16 kg m⁻² to -0.10 kg m⁻².

The C to N ratios (C:N ratios; calculated as %SOC/%TN) under trees were greater than the adjacent farmed fields except at the Corsica East, Marquette, and McPherson sites where farmed fields had higher C:N ratios. The differences in TN and C:N ratio were both higher in the surface soil and decreased with depth.

In all, soil under trees had greater C and N content as compared to the adjacent farmed fields indicating the potential of these tree plantings to add significant amount of C to the soils and at deeper depths. Similar trends of greater SOC under tree plantings were also observed in other studies examining the effect of trees integration into agricultural land use on SOC (Sauer et al. 2007; Hernandez-Ramirez et al. 2011) and at deeper depths (Cardinael et al. 2015).

Greater C and N content under trees as compared to the adjacent fields can be attributed primarily to; higher C inputs from aboveground tree litter and belowground extensive fine root system (Dhillon and Van Rees 2017), which can penetrate deep into the mineral soil (Lorenz and Lal 2014). Trees extensive deep rooting system is considered a critical source of more stable root derived C in subsurface soil layers due to their higher chemical recalcitrance and the physical protection of root hairs within soil aggregates than the shoot derived C (Rasse et al. 2005; Lorenz and Lal 2014; Dhillon and Van Rees 2017).

Other studies attributed the increase in SOC under trees to their microclimate effect. For example, Hernandez-Ramirez et al.(2011) speculated the higher SOC under conifers species was due to their potential to alter soil environments. The presence of tree ground cover, the quantity of litters produced, and the higher water uptake create colder and drier soil environment. The cool and dry soil conditions would reduce OM decomposition rates, therefore increasing the SOC accumulation in soils beneath the tree.

It has been also suggested by other studies that soil texture and mineralogy (Richter et al. 1999; Leggett and Kelting 2006), as well as other soil factors (e.g. temperature, moisture, and C:N ratio) may be contributing to the variation in SOC accrual (Melillo et al. 1989; Richter et al. 1999; Sauer et al. 2007; Kiser et al. 2009; Hernandez-Ramirez et al. 2011).

Windbreaks were designed to reduce wind speed and control wind erosion, which leads to less surface SOC losses. Moreover, Sauer et al. (2007) reported a marked increase in silt and clay content on the leeward side of the tree windbreak, which they attributed to the deposition of windblown sediments on the leeward side of the windbreak, therefore contributed to greater SOC under the trees, however, they concluded that their interpretation while consistent, requires further testing to verify.

In addition, the presence of trees permanent ground cover intercepts raindrops thereby reducing surface SOC loss by physical soil detachment and water erosion (Sauer et al. 2007). Other previous studies also support the hypothesis that the availability of nutrients particularly nitrogen (N), phosphorus (P), and sulfur (S) may limit the SOC sequestration in terrestrial ecosystems (Himes 1998; Lal 2008; Kirkby et al. 2016; Shi et al. 2016). Lower SOC content in the adjacent row crop fields at Milnor, Mead, and McPherson sites may be due to lower C inputs to the soil (e.g. removal of crop biomass), cultivation and tillage. Tillage increases soil aggregates breakdown and disruption leading to SOM decomposition thus SOC loss (West and Post 2002).

Other soil properties

Soil physical and chemical properties were analyzed to provide a more complete interpretation of tree plantation effects on SOC storage and likely to elucidate which of above

processes may have affected the observed pattern of SOC. The general soil properties for soils beneath trees and the adjacent farmed fields are presented in Table 2.3.

Bulk density

Bulk density was consistently lower beneath the trees and in the surface layers. Across all sites, soil bulk density of trees was lower by 6.9 % in the surface 10 cm (1.32 vs. 1.42 g cm^{-3}) as compared to the adjacent farmed fields (Table 2.3, Fig. 2.5). The lower bulk density is expected and was also observed in other studies (Sauer et al. 2007; Hernandez-Ramirez et al. 2011; Cardinael et al. 2015; Dhillon and Van Rees 2017) which can be attributed to the lack of soil compaction due to heavy farm machinery and the presence of grazing animals, higher organic matter resulted from the higher tree above- and below-ground biomass, and soil invertebrates which help in natural ameliorization processes (Sauer et al. 2007; Dhillon and Van Rees 2017).

Water and KCl pH

Average pH values varied by sites and depths. Soil pH under trees and the adjacent farmed fields was lower at the surface and increased with soil depth (Fig. 2.5 and 2.6). The maximum and minimum pH in water values were 8.35 and 8.41 in the 100-125 cm layers beneath honey locust tree and the adjacent farmed fields at Corsica East, respectively, and 4.80 and 5.26 in the 20-30, 10-20 cm layers, respectively, beneath red cedar tree and the adjacent farmed fields at Stromsburg, respectively. Although eastern red cedar has been found to raise soil pH (Sauer et al. 2007), but, in this study, the lowest (most acidic) pH values were found under the red cedar tree at the Stromsburg site and were 5.5, 5.03, and 4.8 in the surface 0-10, 10-20, 20-30 cm layers of soil. Lower pH were found under tree soils (Table 2.3, Fig. 2.5, 2.6). However, higher pH values were observed at the Milnor, Corsica East, Marquette, and McPherson sites with the tree soil pH was 0.7, 0.49, 0.83, and 1.95 units

greater than the adjacent farmed fields at the 0-10 cm layer of soil, respectively, and was only significant at McPherson (Table 2.3). However, both Corsica West and Stromsburg tree soils had significantly lower pH than the adjacent farmed fields (Fig.2.5, 2.6).

In all of the study soils and land-uses, values of pH in 0.01M KCl pH were always lower than those in water (see; Appendix, Fig. S1). This is in general agreement with previous studies reported a lower pH values in 1M KCl than in water (Moore and Loeppert 1987; Thomas 1996).

Aggregate stability

The amount of water stable macroaggregates (soil aggregates > 250 μm diameter) was higher for the surface 0-10 cm under trees (17.40, 44.88, and 61.82%) than the adjacent farmed fields [row crop fields] (12.94, 19.16, and 31.56%) at Mead, McPherson, and Milnor, respectively (Table 2.3, Fig. 2.8). Tillage and cultivation of the row crop fields breakdown soil macroaggregates and inhibits their formation (Márquez et al. 2004). In contrast, the surface 0-10 cm soil layer beneath the adjacent pasture, hay, and grassland at the McLeod, Corsica East, Corsica West and Marquette sites had higher WSA (14.46, 48.03, 57.38, and 57.15%) than the tree soils (10.45, 36.09, 40.61, and 42.97%), respectively. This finding is in general agreement with other studies that reported greater WSA under grasslands than forest and annual cropping systems (Scott 1998; Márquez et al. 2004).

Greater WSA under grasslands as compared to trees could be due to the different mechanisms (e.g. root systems) that affects aggregate formation and stability under each ecosystem (Scott 1998). SOM promotes the formation and stabilization of macroaggregates, thus, the higher WSA beneath trees and grasslands as compared to the row cropped fields can be explained primarily due to higher abundance and decomposition of roots and higher leaf litterfall at the surface layer.

Conclusion

Tree plantings resulted in marked decrease in bulk density and increase in the amount of water stable macroaggregates with no adverse effect on soil pH and soil nutrient content. The results of this study suggest that tree windbreaks will likely improve soil quality and has potential to enhance related ecosystem services associated with C storage.

The higher SOC stocks after trees integration as compared to the adjacent farmed fields is consistent with other studies in the US (Sauer et al. 2007, 2012; Hernandez-Ramirez et al. 2011), Canada (Baah-Acheamfour et al. 2015), Europe (Cardinael et al. 2017), and elsewhere (Takimoto et al. 2009). However, few previous studies have focused on the subsurface SOC (Haile et al. 2008; Cardinael et al. 2015, 2017), and only examined one type of agroforestry (e.g. Haile et al. 2010; Cardinael et al. 2015).

Soils beneath trees averaged $2.93 \pm 2.07 \text{ kg m}^{-2}$ (mean \pm standard error) greater SOC stocks measured to 1.25 m than the adjacent farmed fields. This finding shows the potential of trees to increase SOC storage. The subsurface soil beneath trees and the adjacent farmed fields stored more SOC stocks than the surface soil (9.54 vs. 8.84 kg m^{-2}), (7.85 vs. 7.61 kg m^{-2}), respectively. This finding demonstrates the importance of studying the C stored at deeper depths under tree-based systems when the full capacity of trees SOC sequestration is being assessed.

Ideally, to determine the complete potential for C sequestration under trees, aboveground C should also be taken in consideration. Perhaps, allometric equations should be developed for trees grown outside of forest to reduce the uncertainty of tree biomass estimates. The C quantity assessments need to be supplemented with information about the quality and the turnover of the stored SOC. Perhaps, the examination of SOM fractions

combined with stable isotope analysis for C source assessment, would provide further insights into SOC dynamics under such practices.

Acknowledgment

The authors sincerely appreciate the valuable suggestions of Dr. Cynthia Cambardella and Dr. Guillermo Hernandez-Ramirez, and the field and laboratory assistance of Kevin Jensen, Gavin Simmon, Jody Ohmacht, Jay Berkey, Amy Morrow, and several student workers at the National Laboratory for Agriculture and the Environment. We are grateful for the cooperation of five private landowners, staff with the U.S.D.A. Forest Service and Natural Resources Conservation Service, University of Nebraska-Lincoln Eastern Nebraska Research and Extension Center, and soil and water conservation district staff in Polk County, Nebraska and Douglass County, South Dakota. We acknowledge financial support by North Central Sustainable Agriculture Research and Education project LNC12-346.

References

- Baah-Acheamfour M, Chang SX, Carlyle CN, Bork EW (2015) Carbon pool size and stability are affected by trees and grassland cover types within agroforestry systems of western Canada. *Agric Ecosyst Environ* 213:105–113. doi: 10.1016/j.agee.2015.07.016
- Boussougou INM, Brais S, Tremblay F, Gaussiran S (2010) Soil Quality and Tree Growth in Plantations of Forest and Agricultural Origin. *Soil Sci Soc Am J* 74:993. doi: 10.2136/sssaj2009.0264
- Cardinael R, Chevallier T, Barthès BG, et al (2015) Impact of alley cropping agroforestry on stocks, forms and spatial distribution of soil organic carbon - A case study in a Mediterranean context. *Geoderma* 259–260:288–299. doi: 10.1016/j.geoderma.2015.06.015
- Cardinael R, Chevallier T, Cambou A, et al (2017) Increased soil organic carbon stocks under agroforestry: A survey of six different sites in France. *Agric Ecosyst Environ* 236:243–255. doi: 10.1016/j.agee.2016.12.011

- Cuellar AD, Herzog H (2015) A path forward for low carbon power from biomass. *Energies* 8:1701–1715. doi: 10.3390/en8031701
- Dhillon GS, Van Rees KCJ (2017) Soil organic carbon sequestration by shelterbelt agroforestry systems in Saskatchewan. *Can J Soil Sci* 97:394–409. doi: 10.1139/cjss-2016-0094
- Droze WH (1977) *Trees, prairies, and people – a history of tree planting in the Plains States*. Texas Woman's University, Denton.
- Durkay (2017) State Renewable Portfolio Standards and Goals. In: 2017. <http://www.ncsl.org/research/energy/renewable-portfolio-standards.aspx>
- Garrett (2009) *North American Agroforestry : An Integrated Science and Practice* Madison, WI: American Society of Agronomy. 400 p.
- Gee GW OD (2002) Particle-size analysis. In: Dane JH, Topp GC (eds) *Methods of soil analysis—Part 4 physical methods*. Soil Science Society of America, Madison, pp 255–293. pp 4–5
- Gruenewald H, Brandt BKV, Schneider BU, et al (2007) Agroforestry systems for the production of woody biomass for energy transformation purposes. *Ecol Eng* 29:319–328. doi: 10.1016/j.ecoleng.2006.09.012
- Haile SG, Nair PKR, Nair VD (2008) Carbon Storage of Different Soil-Size Fractions in Florida Silvopastoral Systems. *J Environ Qual* 37:1789. doi: 10.2134/jeq2007.0509
- Haile SG, Nair VD, Nair PKR (2010) Contribution of trees to carbon storage in soils of silvopastoral systems in Florida, USA. *Glob Chang Biol* 16:427–438. doi: 10.1111/j.1365-2486.2009.01981.x
- Hand AM, Bowman T, Tyndall JC (2017) Influences on farmer and rancher interest in supplying woody biomass for energy in the US Northern Great Plains. *Agrofor Syst* 1–14. doi: 10.1007/s10457-017-0170-x
- Harper RJ, Tibbett M (2013) The hidden organic carbon in deep mineral soils. *Plant Soil* 368:641–648. doi: 10.1007/s11104-013-1600-9

- Hernandez-Ramirez G, Sauer TJ, Cambardella C a., et al (2011) Carbon sources and dynamics in afforested and cultivated Corn Belt soils. *Soil Sci Soc Am J* 75:216–225. doi: 10.2136/sssaj2010.0114
- Himes FL (1998) Nitrogen, sulfure, and phosphorus and the sequestering of carbon. In *Soil processes and the carbon cycle* Lal R, Kimble J.M, Follett R.F, Stewart B.A 1998pp. 315–319. Eds. Boca Raton, FL:CRC Press.
- Hudson BD (1994) Soil organic matter and available water capacity. *J Soil Water Conserv* 49:189–194. doi: 10.1081/E-ESS-120018496
- Hulugalle NR, Strong C, McPherson K, Nachimuthu G (2017) Carbon, nitrogen and phosphorus stoichiometric ratios under cotton cropping systems in Australian Vertisols: a meta-analysis of seven experiments. *Nutr Cycl Agroecosystems* 107:357–367. doi: 10.1007/s10705-017-9837-y
- Jackson RB, Canadell J, Ehleringer JR, et al (1996) A global analysis of root distributions for terrestrial biomes. *Oecologia* 108:389–411. doi: 10.1007/BF00333714
- Jackson RB, Mooney HA, Schulze E-D (1997) A global budget for fine root biomass, surface area, and nutrient contents. *Proc Natl Acad Sci* 94:7362–7366. doi: 10.1073/pnas.94.14.7362
- Jose S, Bardhan S (2012) Agroforestry for biomass production and carbon sequestration: An overview. *Agrofor Syst* 86:105–111. doi: 10.1007/s10457-012-9573-x
- Kirkby CA, Kirkegaard JA, Richardson AE, et al (2011) Stable soil organic matter: A comparison of C:N:P:S ratios in Australian and other world soils. *Geoderma* 163:197–208. doi: 10.1016/j.geoderma.2011.04.010
- Kirkby CA, Richardson AE, Wade LJ, et al (2016) Inorganic Nutrients Increase Humification Efficiency and C-Sequestration in an Annually Cropped Soil. *PLoS One* 11:e0153698. doi: 10.1371/journal.pone.015369
- Kirkby CA, Richardson AE, Wade LJ, et al (2013) Carbon-nutrient stoichiometry to increase soil carbon sequestration. *Soil Biol Biochem* 60:77–86. doi: 10.1016/j.soilbio.2013.01.011

- Kiser LC, Kelly JM, Mays P a. (2009) Changes in Forest Soil Carbon and Nitrogen after a Thirty-Year Interval. *Soil Sci Soc Am J* 73:647. doi: 10.2136/sssaj2008.0102
- Lal R (2008) Promise and limitations of soils to minimize climate change. *J Soil Water Conserv* 63:113A–118A. doi: 10.2489/63.4.113A
- Lal R (2009) Challenges and opportunities in soil organic matter research. *Eur J Soil Sci* 60:158–169. doi: 10.1111/j.1365-2389.2008.01114.x
- Langholtz, M. H., Stokes, B. J., & Eaton LM (2016) 2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy. United States. doi:10.2172/1271651.
- Leggett ZH, Kelting DL (2006) Fertilization effects on carbon pools in loblolly pine plantations on two upland sites. *Soil Sci Soc Am J* 70:279–286
- Lorenz K, Lal R (2014) Soil organic carbon sequestration in agroforestry systems. A review. *Agron Sustain Dev* 34:443–454. doi: 10.1007/s13593-014-0212-y
- Malhi SS (2012) Improving organic C and N fractions in a sulfur-deficient soil with S fertilization. *Biol Fertil Soils* 48:735–739. doi: 10.1007/s00374-012-0668-3
- Márquez CO, Garcia VJ, Cambardella CA, et al (2004) Aggregate-Size Stability Distribution and Soil Stability. *Soil Sci Soc Am J* 68:725. doi: 10.2136/sssaj2004.0725
- Mcguire B, Rupp S (2013) Perennial Herbaceous Biomass Production and Harvest in the Prairie Pothole Region of the Northern Great Plains Best Management Guidelines to Achieve Sustainability of Wildlife Resources Perennial Herbaceous Biomass Production and Harvest in the Prairie Po
- Melillo JM, Aber JD, Linkins AE, et al (1989) Carbon and nitrogen dynamics along the decay continuum: Plant litter to soil organic matter. *Ecol Arab L — Perspect Challenges* 198:53–62. doi: 10.1007/978-94-009-1021-8_6
- Miller JR, Morton LW, Engle DM, et al (2012) *Frontiers in Ecology and the Environment* Nature reserves as catalysts for landscape change. *Front Ecol Env*. doi: 10.1890/100227

- Mitchell RB, Schmer MR, Anderson WF, et al (2016) Dedicated Energy Crops and Crop Residues for Bioenergy Feedstocks in the Central and Eastern USA. *Bioenergy Res* 9:384–398. doi: 10.1007/s12155-016-9734-2
- Montagnini F, Nair PKR (2004) Carbon sequestration: An underexploited environmental benefit of agroforestry systems. *Agrofor Syst* 61–62:281–295. doi: 10.1023/B:AGFO.0000029005.92691.79
- Moore TJ, Loeppert RH (1987) Significance of Potassium Chloride pH of Calcareous Soils1. *Soil Sci Soc Am J* 51:908. doi: 10.2136/sssaj1987.03615995005100040014x
- Nair PKR (2012) Carbon sequestration studies in agroforestry systems: A reality-check. *Agrofor Syst* 86:243–253. doi: 10.1007/s10457-011-9434-z
- Nair PKR, Nair VD, Kumar B, Showalter JM (2010) Carbon sequestration in agroforestry systems. *Adv Agron* 108:237–307. doi: 10.1016/S0065-2113(10)08005-3
- Paul KI, Polglase PJ, Khanna PK, et al (2002) Change in Soil Carbon Following Afforestation or Reforestation. *Office* 168:117. doi: Pii S0378-1127(01)00740-X\rDoi 10.1016/S0378-1127(01)00740-X
- Qingwu Xue GW and PEN (2013) Biomass Production in Northern Great Plains of USA – Agronomic Perspective, Biomass Now Miodrag Darko Matovic, IntechOpen, DOI: 10.5772/52917. Available from: doi: <http://dx.doi.org/10.5772/46845>
- Rasse DP, Rumpel C, Dignac MF (2005) Is soil carbon mostly root carbon? Mechanisms for a specific stabilisation. *Plant Soil* 269:341–356. doi: 10.1007/s11104-004-0907-y
- Read R. (1958) The Great Plains shelterbelts in 1954. Great Plains Agricultural Council, Lincoln, NE, USA. Publication No. 16.
- Ren C, Zhao F, Kang D, et al (2016) Linkages of C:N:P stoichiometry and bacterial community in soil following afforestation of former farmland. *For Ecol Manage* 376:59–66. doi: 10.1016/j.foreco.2016.06.004
- Richter DD, Markewitz D, Trumbore SE, Wells CG (1999) Rapid accumulation and turnover of soil carbon in a re-establishing forest. *Nature* 400:56–58. doi: 10.1038/21867

Rosenberg NJ (2007) A biomass future for the North American Great Plains. 49:218. doi: 10.1007/978-1-4020-5601-7

Rosenberg NJ, Smith SJ (2009) A sustainable biomass industry for the North American Great Plains. *Curr Opin Environ Sustain* 1:121–132. doi: 10.1016/j.cosust.2009.09.003

Sauer TJ, Cambardella CA, Brandle JR (2007) Soil carbon and tree litter dynamics in a red cedar-scotch pine shelterbelt. *Agrofor Syst* 71:163–174. doi: 10.1007/s10457-007-9072-7

Sauer TJ, Coblenz WK, Thomas AL, et al (2015) Nutrient cycling in an agroforestry alley cropping system receiving poultry litter or nitrogen fertilizer. *Nutr Cycl Agroecosystems* 101:167–179. doi: 10.1007/s10705-014-9667-0

Sauer TJ, James DE, Cambardella CA, Hernandez-Ramirez G (2012) Soil properties following reforestation or afforestation of marginal cropland. *Plant Soil* 360:375–390. doi: 10.1007/s11104-012-1258-8

Schoeneberger MM (2009) Agroforestry: Working trees for sequestering carbon on agricultural lands. *Agrofor Syst* 75:27–37. doi: 10.1007/s10457-008-9123-8

Schoenholtz S., Miegroet HV, Burger J. (2000) A review of chemical and physical properties as indicators of forest soil quality: challenges and opportunities. *For Ecol Manage* 138:335–356. doi: 10.1016/S0378-1127(00)00423-0

Schroeder P (1994) Carbon storage benefits of agroforestry systems. *Agrofor Syst* 27:89–97. doi: 10.1007/BF00704837

Scott NA (1998) Soil aggregation and organic matter mineralization in forests and grasslands: plant species effects. *Soil Sci Soc Am J* 62:1081–1089

Sherrod LA, Dunn G, Peterson GA, Kolberg RL (2002) Inorganic Carbon Analysis by Modified Pressure-Calcimeter Method. *Soil Sci Soc Am J* 66:299. doi: 10.2136/sssaj2002.2990

- Shi S, Peng C, Wang M, et al (2016) A global meta-analysis of changes in soil carbon, nitrogen, phosphorus and sulfur, and stoichiometric shifts after forestation. *Plant Soil* 407:323–340. doi: 10.1007/s11104-016-2889-y
- Soil Survey Laboratory Staff, Government Printing Office DC W, Soil Survey Division Staff (1996) *Soil Survey Laboratory Methods Manual*
- Takimoto A, Nair VD, Nair PKR (2009) Contribution of trees to soil carbon sequestration under agroforestry systems in the West African Sahel. *Agrofor Syst* 76:11–25. doi: 10.1007/s10457-008-9179-5
- Teepe R, Dilling H, Beese F (2003) Estimating water retention curves of forest soils from soil texture and bulk density. *J Plant Nutr Soil Sci* 166:111–119. doi: 10.1002/jpln.200390001
- Thomas GW (1996) Soil pH and soil acidity. *Methods soil Anal Part 3 - Chem methods* 475–490. doi: 10.1007/978-94-6091-478-2_16
- Tyndall JC, Schulte LA, Hall RB, Grubh KR (2011) Woody biomass in the U.S. Cornbelt? Constraints and opportunities in the supply. *Biomass and Bioenergy* 35:1561–1571. doi: 10.1016/j.biombioe.2010.12.028
- U.S. Forest Service. (1935) U.S. Forest Service. 1935. Possibilities of shelterbelt planting in the Plains region. Lake States Forest Experiment Station Special Publication. 201 pp.
- Udawatta RP, Adhikari P, Anoma Senaviratne GMMM, Garrett HE (2015) Variability of soil carbon in row crop watersheds with agroforestry buffers. *Agrofor Syst* 89:37–47. doi: 10.1007/s10457-014-9740-3
- USDOE (2011) U.S. billion-ton update: biomass supply for a bioenergy and bioproducts industry. Agricultural and biosystems engineering technical reports and white papers
- West TO, Post WM (2002) Soil Organic Carbon Sequestration Rates by Tillage and Crop Rotation : A Global Data Analysis. *Soil Sci Soc Am J* 66:1930–1946. doi: 10.2136/sssaj2002.1930

Table 2.1 Summary of field locations. Precipitation and temperature data are 30-yr normals from the nearest weather station (National Oceanic and Atmospheric Administration 2002)

Site	MAP (mm)	MAT (°C)	Tree Species & age (years)	Crop (years)	Soil (USDA Classification)	Number of rows	Other species	Orientation
McLeod, ND	22.43	43.2	Ponderosa pine (80) <i>Pinus ponderosa</i>	Pasture (80)	Hecla loamy fine sand (Sandy, mixed, frigid Oxyaquic Hapludolls)	2	Caragana and ash	West- East
Milnor, ND	23.31	43.2	Elm (50+) <i>Ulmus pumila</i>	Row crop (135)	Forman clay loam (Fine-loamy, mixed, superactive, frigid Calcic Argiudolls)	12	Ash, caragana, cedar, and cottonwood	West-East
Corsica East, SD	24.94	49	Honey locust (15) <i>Gleditsia triacanthos</i>	Hay (15)	Eakin silt loam (Fine- silty, mixed, superactive, mesic Typic Argiustolls)	9	Cottonwood, sugar maple, black walnut, plum, red cedar,	West-East
Corsica West, SD	24.94	49	Green ash (25) <i>Fraxinus pennsylvanica</i>	Pasture (125)	Eakin silt loam (Fine- silty, mixed, superactive, mesic Typic Argiustolls)	2	Plum, hackberry, apricot scotch pine, Russian olive, red cedar	West-East
Mead, NE	29.39	49.9	Green ash ~ (40) <i>Fraxinus pennsylvanica</i>	Row crop (125)	Tomek silt loam (Fine, smectitic, mesic Pachic Argiudolls)	2	Red cedar, honeysuckle, and Australian pine	North-South
Stromsburg, NE	30.23	50.4	Red cedar (21) <i>Juniperus virginiana</i>	Alfalfa (10)	Hastings silt loam (Fine, smectitic, mesic Udic Argiustolls)	2	Red mulberry	East-West
Marquette, KS	32.97	55.1	Black locust (29) <i>Robinia pseudoacacia</i>	Grassland (29)	Irwin loam (Fine, mixed, superactive, mesic Pachic Argiustolls)	2	Red cedar	North-South
McPherson, KS	32.97	55.1	Osage orange (90+) <i>Maclura pomifera</i>	Row crop (115)	Irwin silty clay loam (Fine, mixed, superactive, mesic Pachic Argiustolls)	1	Hackberry	North-South

Table 2.2 Weighted mean of soil C and N for the surface (0-30 cm), subsurface (30-125 cm), and the entire soil profile (0-125 cm) beneath the trees and the adjacent farmed fields in the U.S. Great Plains.

	Depth (cm)	McLeod		Milnor		Corsica E		Corsica W	
		Ponderosa pine	Pasture	Elm	Row crop	Honey locust	Hay	Green ash	Pasture
SOC (g kg ⁻¹)	0-30	16.02	11.87	41.83	25.84	15.06**	19.37**	28.89	27.27
	30-125	4.30	4.07	7.15	3.85	5.07	6.33	12.02**	6.18**
	0-125	7.12	5.94	15.48	9.13	7.47*	9.46*	16.07**	11.24**
TN (g kg ⁻¹)	0-30	1.20	1.10	3.58	2.36	1.37*	1.69*	2.64	2.58
	30-125	0.41	0.41	0.73	0.53	0.49	0.54	1.09**	0.65**
	0-125	0.60	0.58	1.41	0.97	0.70*	0.82*	1.47*	1.11*
SOC (kg m ⁻²)	0-30	6.61	4.92	15.51	10.64	6.12**	8.12**	9.96	10.64
	30-125	5.92	5.46	9.74	5.21	6.85	8.80	16.66**	8.60**
	0-125	12.53	10.38	25.25	15.85	12.97**	16.92**	26.20*	19.25*
TN (kg m ⁻²)	0-30	0.50	0.46	1.33	0.97	0.56	0.71	0.91	1.01
	30-125	0.56	0.55	1.00	0.72	0.67	0.76	1.51	0.91
	0-125	1.06	1.01	2.32	1.69	1.22	1.46	2.42	1.92
C:N	0-30	12.98*	10.86*	11.74*	10.95*	11.08	11.37	10.94	10.68
	30-125	10.52	9.89	8.26	6.83	10.27	12.26	11.22	9.21
	0-125	11.11	10.12	9.10	7.82	10.46	12.05	11.16	9.57

Means for samples from trees and the adjacent fields within each depth at each site followed by *, **, or *** indicate significant differences at or < *p* 0.05, 0.01, 0.001 probability level respectively as determined by the two Sample t test.

Table2.2 Continued weighted mean of soil C and N for the surface (0-30 cm), subsurface (30-125 cm), and the entire soil profile (0-125 cm) beneath the trees and the adjacent farmed fields in the U.S. Great Plains.

	Depth (cm)	Mead		Stromsburg		Marquette		McPherson	
		Green ash	Row crop	Red cedar	Alfalfa	Black locust	Grassland	Osage orange	Row crop
SOC (g kg ⁻¹)	0-30	21.85*	18.27*	21.36	18.43	12.37	11.81	22.98*	12.03*
	30-125	6.03***	10.99***	7.87	6.66	3.00	3.20	9.77**	4.66**
	0-125	9.83**	12.74**	11.10	9.49	5.25	5.27	12.94**	6.43**
TN (g kg ⁻¹)	0-30	1.89*	1.73*	1.91	1.82	0.69	0.43	1.81*	0.90*
	30-125	0.78**	1.12**	0.91	0.80	0.23	0.23	0.82*	0.42*
	0-125	1.05**	1.27**	1.15	1.04	0.34	0.28	1.06*	0.54*
SOC (kg m ⁻²)	0-30	9.30*	7.98*	8.44	7.71	5.73	5.37	9.08*	5.47*
	30-125	7.65***	14.02***	10.82	8.66	4.76	5.08	13.87**	6.93**
	0-125	16.95**	22.00**	19.27	16.37	10.50	10.45	22.95**	12.41**
TN (kg m ⁻²)	0-30	0.80*	0.76*	0.76	0.76	0.32	0.20	0.72*	0.41*
	30-125	0.98**	1.43**	1.25	0.82	0.37	0.36	1.18*	0.50*
	0-125	1.79**	2.18**	2.01	1.58	0.69	0.56	1.86*	0.91*
C:N	0-30	11.47	10.56	11.11*	10.12*	51.45¥	60.83¥	13.00	13.58
	30-125	7.17***	9.71***	7.92	7.70	18.95¥	19.13¥	11.54	11.54
	0-125	8.20	9.91	8.68	8.28	26.75¥	29.14¥	11.89	12.03

Means for samples from trees and the adjacent fields within each depth at each site followed by *, **, or *** indicate significant differences at or $< p$ 0.05, 0.01, 0.001 probability level respectively as determined by the two Sample t test.

¥ C:N ratio value is high at this site as total nitrogen was undetectable and very small in some samples.

Table 2.3. Weighted mean values of soil properties for the surface and subsurface soil, and the entire soil profile (0-125 cm) under the trees and adjacent farmed fields. Sand, silt, and clay content are average of 0-30 and 30-125 cm soil depth

	Depth (cm)	McLeod		Milnor		Corsica E		Corsica W	
		Ponderosa pine	Pasture	Elm	Row crop	Honey locust	Hay	Green ash	Pasture
Sand (%)	0-30	91.03	87.49	33.29	34.91	15.87	12.56	13.13	20.36
	30-125	89.99	86.34	41.23	42.90	45.15	18.31	10.07	22.08
Silt (%)	0-30	8.37	8.73	37.21	32.70	49.64	56.27	63.07	50.15
	30-125	5.27	10.11	36.31	29.74	34.54	52.10	56.55	52.39
Clay (%)	0-30	0.61	3.78	29.49	32.39	34.49	31.17	23.8	29.49
	30-125	4.74	3.55	22.46	27.36	20.31	29.59	33.38	25.54
H ₂ O pH	0-30	6.39	6.60	7.29	6.80	7.25	7.03	6.28*	6.91*
	30-125	7.86**	6.99**	7.66	8.06	8.22	8.23	7.39**	8.10**
	0-125	7.51*	6.90*	7.57	7.75	7.99	7.94	7.12**	7.81**
KCl pH	0-30	5.70	5.89	6.44	6.01	6.27	6.16	5.38*	6.14*
	30-125	7.05**	6.06**	6.99	7.12	7.32	7.47	6.23***	7.31***
	0-125	6.73*	6.02*	6.86	6.85	6.07	7.15	6.03**	7.03**
Bulk Density	10	1.37	1.39	1.16	1.36	1.35	1.43	1.12	1.29
	30	1.41	1.35	1.45	1.40	1.37	1.32	1.22	1.34
	75	1.43	1.39	1.41	1.36	1.41	1.46	1.56	1.58
	100	1.50	1.51	1.46	1.56	1.40	1.50	1.55	1.50
WSA %	0-10	10.45	14.46	61.82	31.56	36.09	48.03	40.61	57.38
	10-20	5.04	6.02	53.88	34.96	40.29	49.51	35.71	48.35
	20-30	4.05	3.28	47.79	45.47	39.47	41.24	32.55	41.36

Means for samples from trees and the adjacent fields within each depth at each site followed by *, **, or *** indicate significant differences at or < *p* 0.05, 0.01, 0.001 respectively as determined by the two Sample t test.

Table 2.3. Continued weighted mean values of soil properties for the surface and subsurface soil, and the entire soil profile (0-125 cm) under the trees and the adjacent farmed fields. Sand, silt, and clay content are average of 0-30 and 30-125 cm soil depth

	Depth (cm)	Mead		Stromsburg		Marquette		McPherson	
		Green ash	Row crop	Red cedar	Alfalfa	Black locust	Grass land	Osage orange	Row crop
Sand (%)	0-30	7.5	4.01	10.73	10.27	30.46	35.31	6.94	6.00
	30-125	6.53	4.71	12.18	9.60	55.24	45.43	5.03	5.40
Silt (%)	0-30	61.20	64.68	67.29	63.50	46.90	32.89	58.95	55.31
	30-125	56.65	63.45	54.63	55.96	19.95	27.15	51.23	52.35
Clay (%)	0-30	31.31	31.31	21.98	26.23	22.63	31.85	34.11	38.69
	30-125	36.82	31.84	33.19	34.45	24.81	27.46	43.75	42.26
pH (water)	0-30	6.34	6.53	5.11*	5.42*	6.04	5.83	7.47**	5.58**
	30-125	6.87	6.70	5.84	6.39	6.38	6.46	6.88*	7.66*
	0-125	6.74	6.66	5.67	5.16	6.30	6.31	7.02	7.16
pH (KCl)	0-30	5.48	5.44	4.13	4.48	5.07*	4.77*	6.60**	4.59**
	30-125	5.99*	5.28*	4.69	5.04	5.05	5.16	5.94	6.58
	0-125	5.87*	5.32*	4.55*	4.91*	5.06	5.06	6.10	6.10
Bulk Density	10	1.45	1.47	1.30	1.45	1.54	1.51	1.30	1.44
	30	1.34	1.42	1.37	1.26	1.55	1.54	1.36	1.51
	75	1.37	1.30	1.51	1.41	1.79	1.78	1.50	1.55
	100	1.24	1.33	1.49	1.52	1.71	1.70	1.71	1.58
WSA %	0-10	17.40	12.94	20.75	12.76	42.98	57.25	44.87	19.16
	10-20	12.13	13.07	17.06	12.83	27.97	52.44	33.22	38.54
	20-30	20.51	10.93	15.91	10.45	28.02	37.76	34.32	51.83

Means for samples from trees and the adjacent fields within each depth at each site followed by *, **, or *** indicate significant differences at or $< p$ 0.05, 0.01, 0.001 respectively as determined by the two Sample t test.

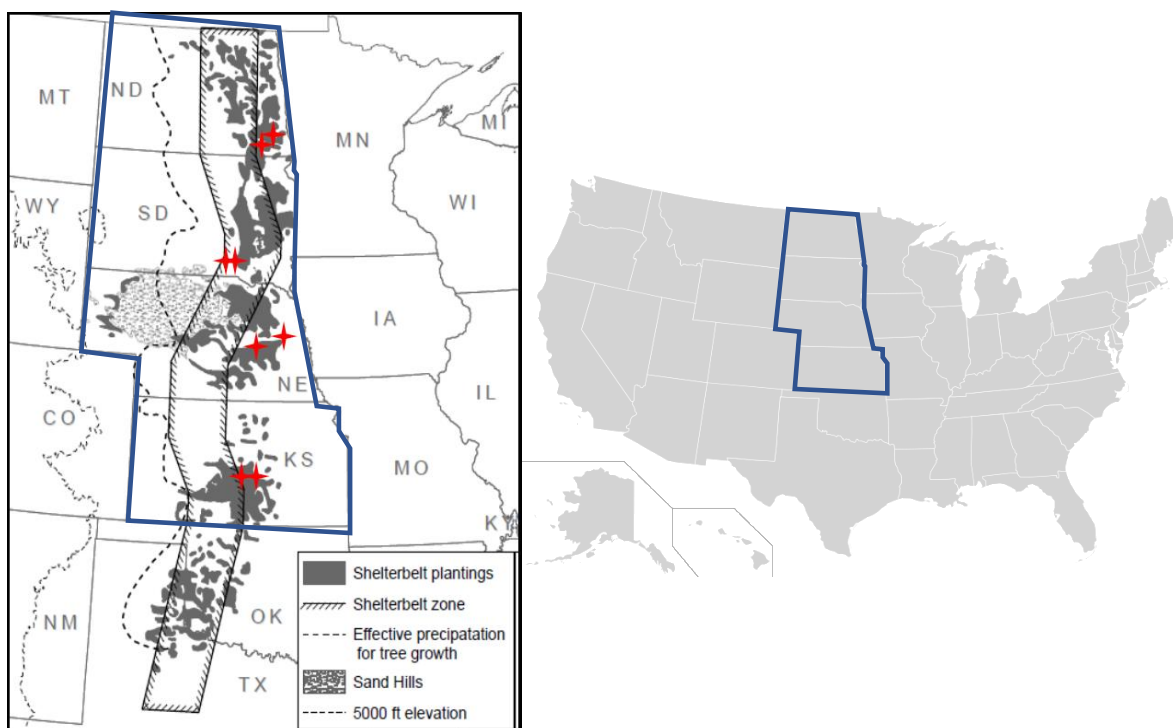


Figure 2.1. Location of the four Northern Great Plains states involved in the study. Red stars denote study soil sampling locations. Other data shows areas of original Prairie States Forestry Project shelterbelt plantings of the 1930s (adapted from (Read, 1958) with overlay of original shelterbelt planting zone as proposed in U.S. Forest Service (1935) for proposed sampling locations).

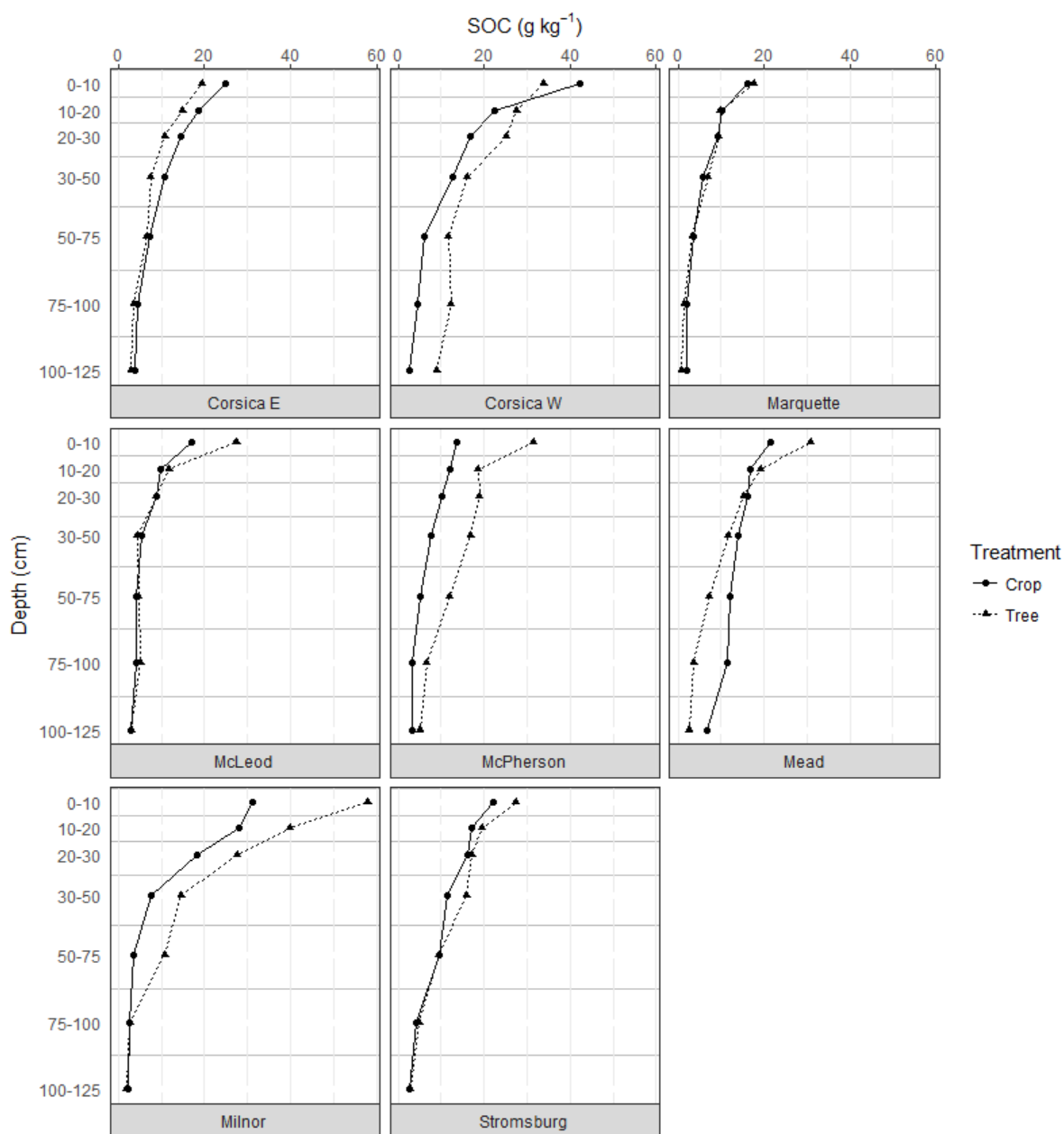


Figure 2.2. Soil organic carbon (SOC) concentration with depth under trees and the adjacent farmed fields (crop) for all study locations in the U.S. Great Plains.

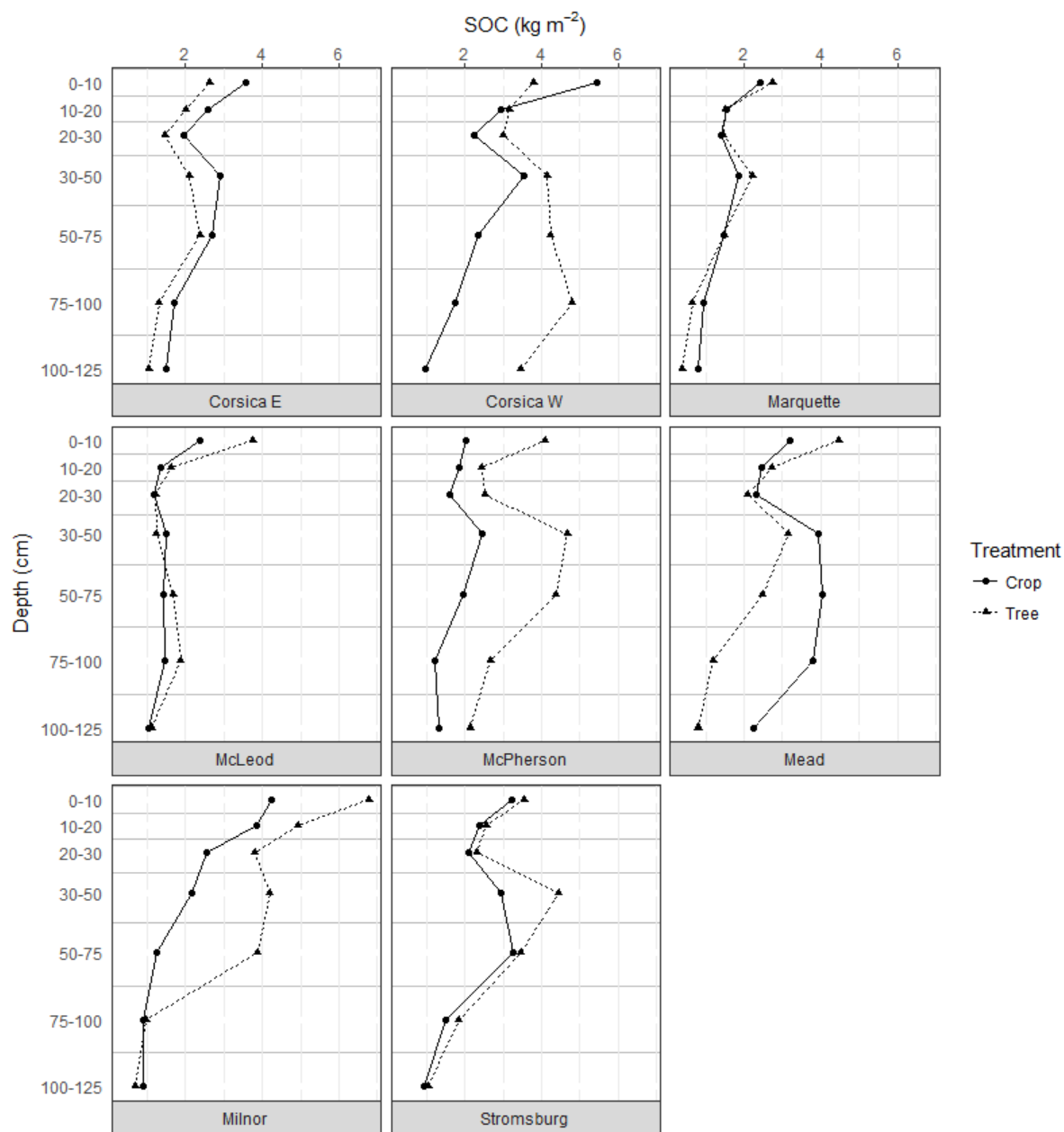


Figure 2.3. Soil organic carbon (SOC) stocks with depth under trees and the adjacent farmed fields (crop) for all study locations in the U.S. Great Plains.

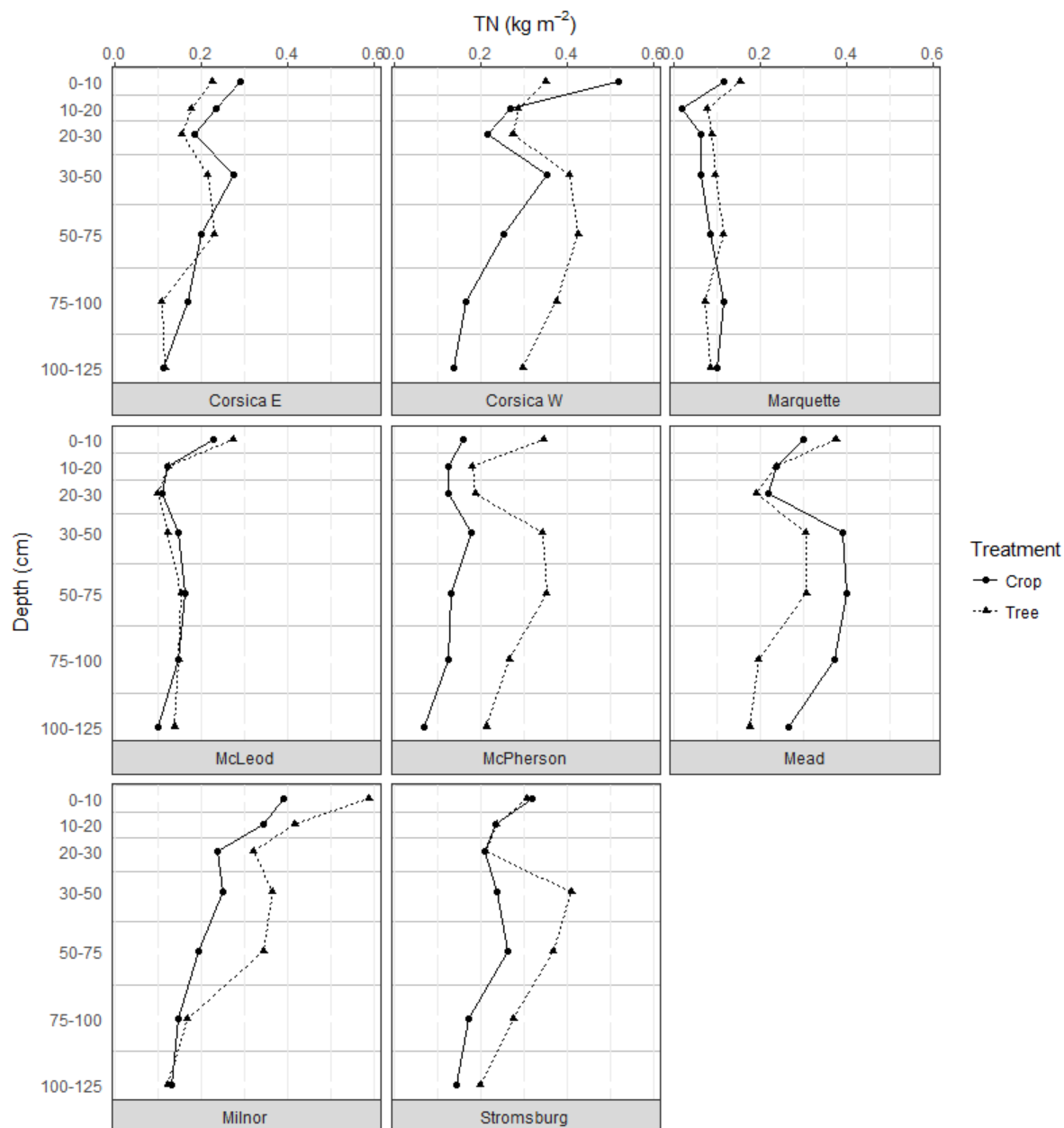


Figure 2.4. Total nitrogen (TN) content with depth under trees and the adjacent farmed fields (crop) for all study locations in the U.S. Great Plains.

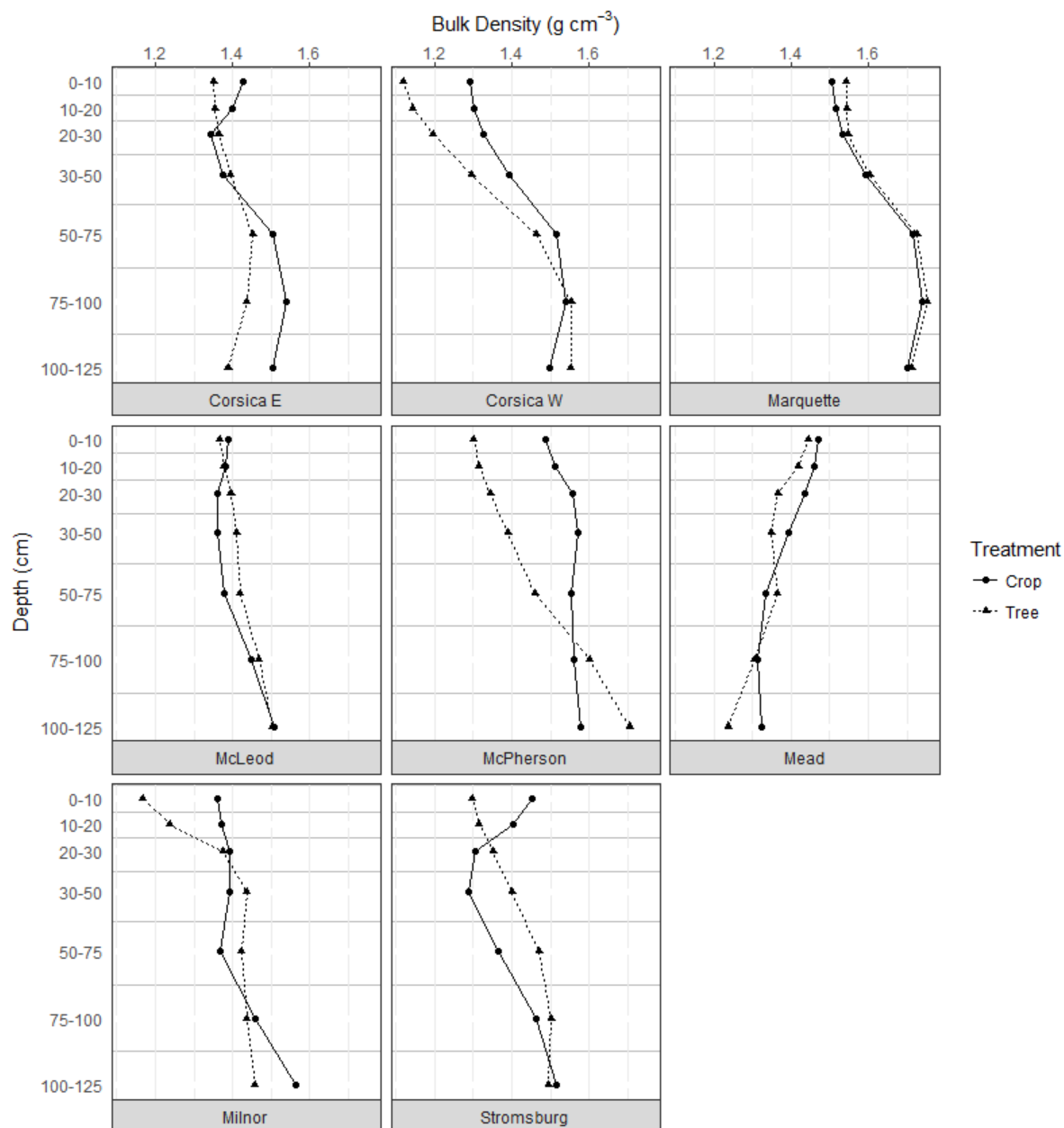


Figure 2.5. Bulk density with depth under trees and the adjacent farmed fields (crop) for all study locations in the U.S. Great Plains.

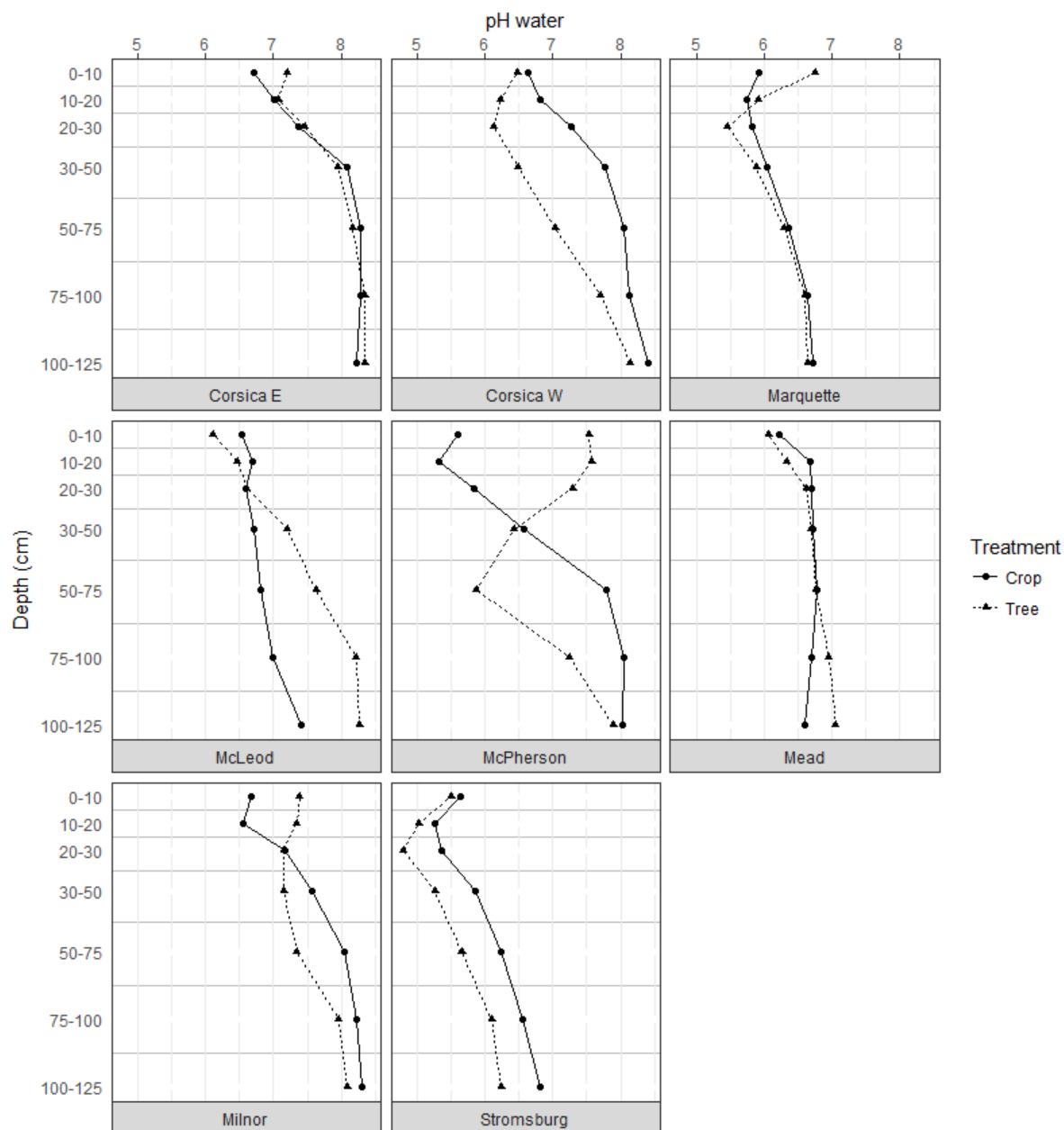


Figure 2.6. pH in water (1:1) with depth under trees and the adjacent farmed fields (crop) for all study locations in the U.S. Great Plains.

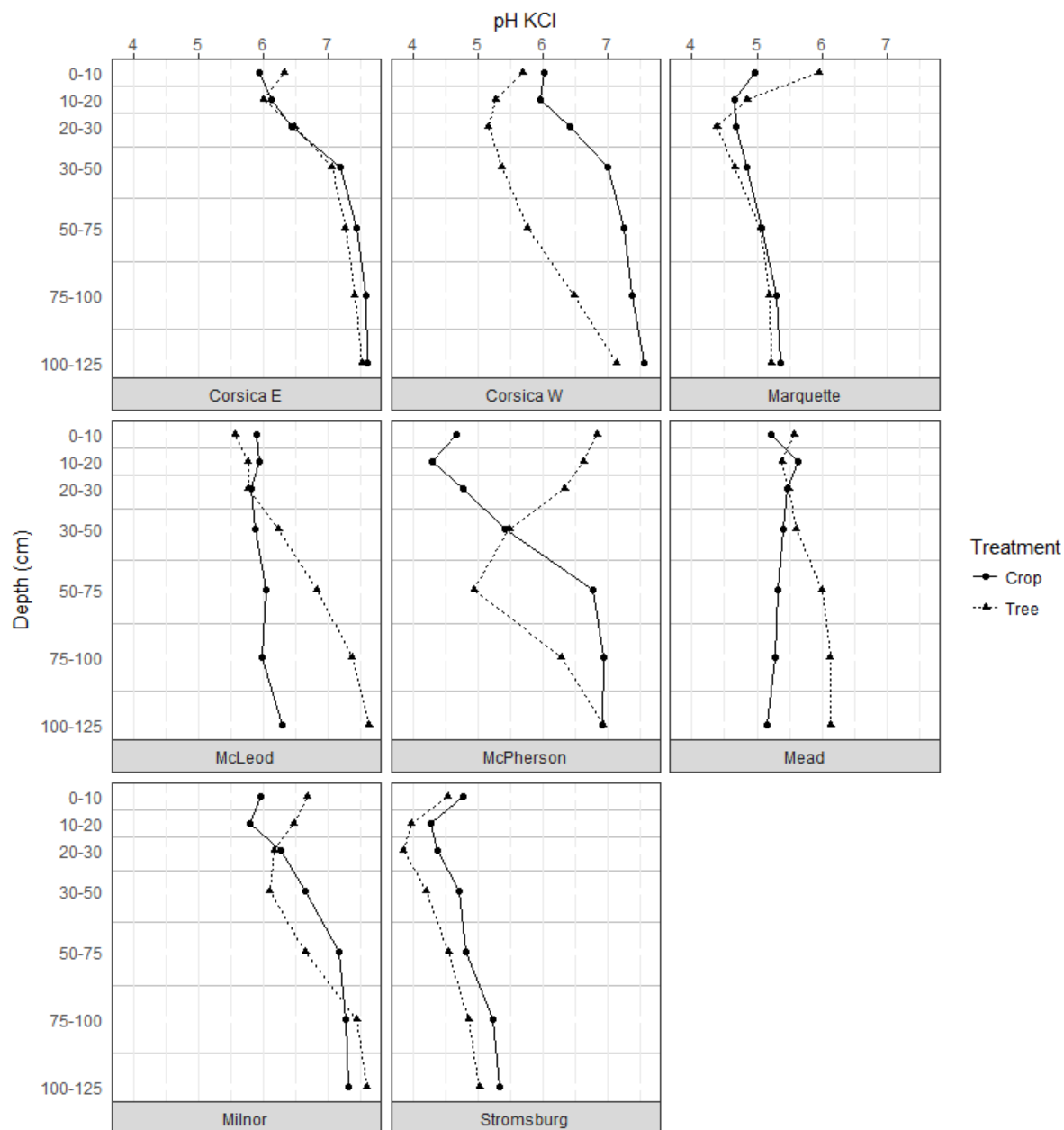


Figure 2.7. pH in KCl (1:1) with depth under trees and the adjacent farmed fields (crop) for all study locations in the U.S. Great Plains.

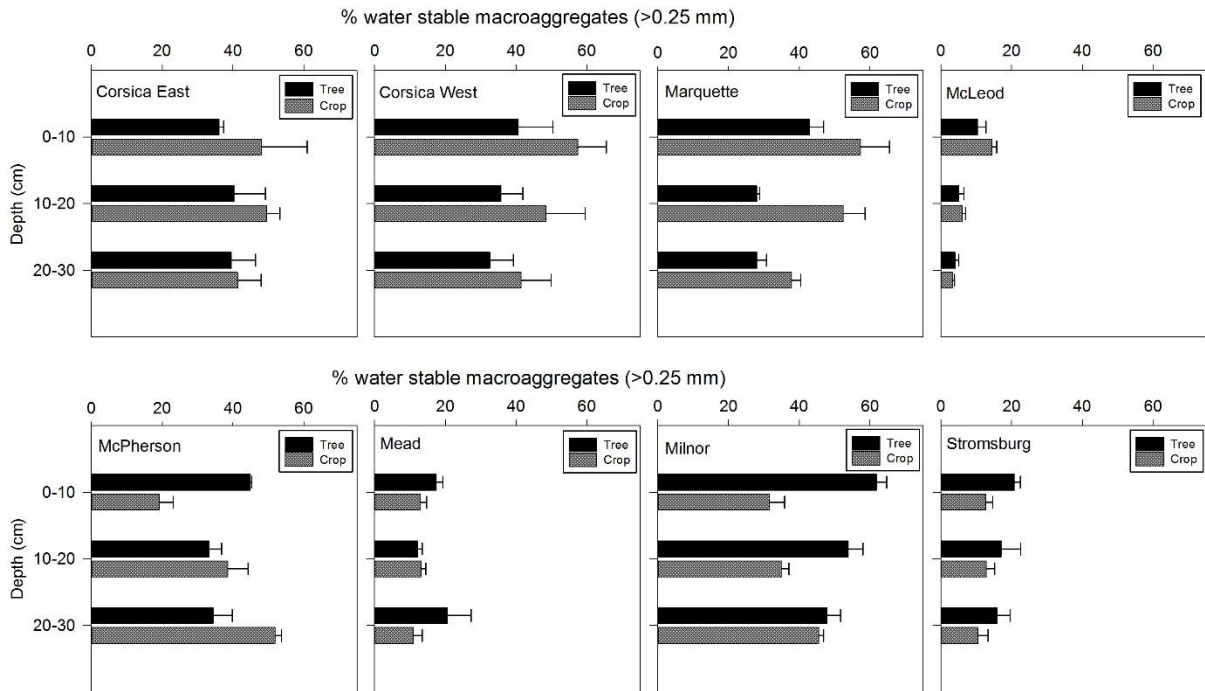


Figure 2.8. Amount of water stable aggregates (>0.25mm) for the surface 0-30 cm layer of soil under trees and the adjacent farmed fields (crop) for all study locations in the U.S. Great Plains. Error bars are one standard error.

Appendix Supplement Data

Table S1. Mean values of soil organic carbon concentrations (g kg^{-1}) and stocks (kg m^{-2}) in each soil depth increments beneath the trees and the adjacent farmed fields in the U.S. Great Plains.

	Depth (cm)	McLeod		Milnor		Corsica E		Corsica W	
		Ponderosa pine	Pasture	Elm	Row crop	Honey locust	Hay	Green ash	Pasture
SOC concentration (g C kg^{-1})	0-10	27.43	17.07	58.00	31.13	19.50	25.07	33.90	42.30
	10-20	11.80	9.73	39.87	28.07	14.87	18.50	27.60	22.60
	20-30	8.83	8.80	27.63	18.33	10.80	14.53	25.17	16.90
	30-50	4.40	5.57	14.57	7.73	7.53	10.63	16.03	12.70
	50-75	4.77	4.17	10.90	3.67	6.57	7.17	11.60	6.20
	75-100	5.10	4.03	2.73	2.43	3.63	4.40	12.33	4.50
	100-125	2.97	2.80	1.90	2.33	3.03	3.97	8.93	2.63
SOC stock (kg m^{-2})	0-10	3.75	2.37	6.78	4.24	2.64	3.58	3.79	5.46
	10-20	1.62	1.34	4.93	3.85	2.02	2.59	3.16	2.94
	20-30	1.23	1.20	3.80	2.55	1.47	1.95	3.01	2.24
	30-50	1.24	1.51	4.19	2.15	2.10	2.92	4.16	3.54
	50-75	1.69	1.43	3.88	1.25	2.39	2.70	4.24	2.35
	75-100	1.87	1.46	0.98	0.89	1.31	1.70	4.79	1.73
	100-125	1.12	1.05	0.69	0.91	1.05	1.49	3.47	0.99

Table S1. Continued

	Depth (cm)	Mead		Stromsburg		Marquette		McPherson	
		Green ash	Row crop	Red cedar	Alfalfa	Black locust	Grass land	Osage orange	Row crop
SOC concentration (g C kg ⁻¹)	0-10	30.97	21.70	27.37	22.17	17.77	16.07	31.47	13.57
	10-20	19.23	16.87	19.47	17.03	9.87	10.23	18.60	12.20
	20-30	15.37	16.23	17.23	16.10	9.47	9.13	18.87	10.33
	30-50	11.70	14.10	15.87	11.47	6.93	5.83	16.83	7.80
	50-75	7.27	12.13	9.43	9.53	3.43	3.47	11.97	5.00
	75-100	3.70	11.57	4.93	4.10	1.50	2.13	6.67	3.13
	100-125	2.60	6.80	2.83	2.50	0.93	1.90	5.03	3.33
SOC stock (kg m ⁻²)	0-10	4.47	3.19	3.55	3.22	2.74	2.42	4.09	2.02
	10-20	2.73	2.46	2.56	2.39	1.52	1.55	2.45	1.84
	20-30	2.10	2.33	2.33	2.10	1.47	1.40	2.54	1.61
	30-50	3.16	3.93	4.44	2.96	2.22	1.86	4.68	2.45
	50-75	2.48	4.04	3.47	3.25	1.48	1.49	4.30	1.94
	75-100	1.21	3.79	1.85	1.50	0.66	0.93	2.67	1.22
	100-125	0.80	2.25	1.06	0.95	0.40	0.81	2.15	1.31

Table S2. Soil profiles description for the study sites.

Site

McLeod, Tree windbreak. Described by: Keith Anderson
ND

MADDOCK SERIES

TAXONOMIC CLASS: Sandy, mixed, frigid Entic Hapludolls

Colors are for moist soil unless otherwise stated.

A1--0 to 10 cm; very dark gray (10YR 3/1) loamy fine sand, dark gray (10YR 4/1) dry; weak fine granular structure; very friable; many fine, and common medium and coarse roots; abrupt smooth boundary.

A2--10 to 20 cm; very dark gray (10YR 3/1) loamy fine sand, very dark grayish brown (10YR 3/2) dry; moderate medium subangular blocky structure; very friable; few fine to coarse roots; clear smooth boundary.

Bw--20 to 61 cm; very dark grayish brown (10YR 3/2) loamy fine sand, dark grayish brown (10YR 4/2) dry; weak medium subangular blocky structure; very friable; few fine to very coarse roots; clear smooth boundary.

Ab--61 to 101 cm; very dark gray (10YR 3/1) loamy fine sand; moderate medium subangular blocky structure; very friable; very few medium and few coarse roots; clear smooth boundary.

C1--101 to 127 cm; dark grayish brown (10YR 4/2) sand; single grain; loose; very few medium and coarse roots; gradual smooth boundary.

C2—127 to 152 cm; dark grayish brown (2.5Y 4/2) sand; single grain; loose; common fine prominent dark yellowish brown (10YR 4/6) redoximorphic concentrations; common fine distinct black (10YR 2/1) soft masses of iron-manganese; very few medium roots; clear smooth boundary.

2C3—152 to 200 cm; dark grayish brown (2.5Y 4/2) stratified very fine sandy loam and fine sand; massive with stratification due to the depositional nature of the parent material; few fine distinct olive brown (2.5Y 4/4) redoximorphic concentrations; strong effervescence.

Table S2. Continued

McLeod,
ND

Pasture. Described by: Keith Anderson

HECLA SERIES

TAXONOMIC CLASS: Sandy, mixed, frigid Oxyaquic Hapludolls

Colors are for moist soil unless otherwise stated.

A1--0 to 7 cm; black (10YR 2/1) loamy fine sand, dark gray (10YR 4/1) dry; weak fine granular structure; very friable; many fine roots; abrupt smooth boundary.

A2--7 to 37 cm; black (10YR 2/1) loamy fine sand, dark gray (10YR 4/1) dry; weak medium prismatic structure parting to weak fine subangular blocky; very friable; common fine roots; gradual wavy boundary.

Bw--37 to 60 cm; very dark gray (10YR 3/1) fine sand, dark grayish brown (10YR 4/2) dry; weak medium prismatic structure parting to weak fine subangular blocky; very friable; few fine roots; abrupt smooth boundary.

Ab--60 to 89 cm; very dark gray (2.5Y 3/1) loamy fine sand; weak medium prismatic structure parting to single grain; very friable; few fine roots; gradual smooth boundary.

AC--89 to 114 cm; very dark grayish brown (2.5Y 3/2) and dark olive brown (2.5Y 3/3) loamy fine sand; single grain; loose; many coarse distinct dark brown (10YR 3/3) redoximorphic concentrations; very few fine roots; gradual smooth boundary.

C1--114 to 156 cm; dark grayish brown (2.5Y 4/2) loamy fine sand; single grain; loose; common fine distinct dark yellowish brown (10YR 4/4) redoximorphic concentrations; few fine distinct black (10YR 2/1) soft masses of iron-manganese; very few fine roots; clear wavy boundary.

2C2--156 to 200 cm; light brownish gray (2.5Y 6/2) stratified very fine sandy loam and fine sand; massive with stratification due to the depositional nature of the parent material; very friable; common fine distinct light olive brown (2.5Y 5/4) redoximorphic concentrations and many fine faint gray (2.5Y 6/1) depletions; violent effervescence.

Table S2. Continued

Milnor, ND Tree windbreak. Described by: Keith Anderson

FORMAN SERIES

TAXONOMIC CLASS: Fine-loamy, mixed, superactive, frigid Calcic Argiudolls

Colors are moist soil unless otherwise stated.

A--0 to 17 cm; black (10YR 2/1) loam, very dark gray (10YR 3/1) dry; moderate medium subangular structure parting to strong fine granular; friable; common fine and medium, and few coarse roots; clear smooth boundary.

Bt1--17 to 28 cm; black (10YR 2/1) loam, very dark grayish brown (10YR 3/2) dry; moderate coarse prismatic structure parting to strong fine subangular blocky; friable; many faint very dark gray (10YR 3/1) clay films on faces of peds; few fine to coarse roots; clear smooth boundary.

Bt2--28 to 49 cm; olive brown (2.5Y 4/3) clay loam; moderate medium prismatic structure parting to strong medium subangular blocky; friable; many faint very dark gray (10YR 3/1) clay films on faces of peds; few medium to very coarse roots; clear smooth boundary.

Bk1--49 to 72 cm; light olive brown (2.5Y 5/4) clay loam; moderate coarse subangular blocky structure parting to moderate fine subangular blocky; friable; few medium distinct pale yellow (2.5Y 7/3) soft masses of carbonates; very few medium, and few coarse and very coarse roots; about 2 percent gravel; violent effervescence; abrupt smooth boundary.

Bk2--72 to 82 cm; light olive brown (2.5Y 5/6) loam; weak fine subangular blocky structure; very friable; very few medium to very coarse roots; about 5 percent gravel; violent effervescence; abrupt wavy boundary.

2Bk3--82 to 102 cm; light olive brown (2.5Y 5/4) clay loam; weak coarse subangular blocky structure parting to moderate fine and medium subangular blocky; friable; few fine distinct grayish brown (2.5Y 5/2) depletions; very few medium roots; about 2 percent gravel; violent effervescence; clear wavy boundary.

Table S2. Continued

Milnor, ND **Row crop field. Described by: Keith Anderson**

FORMAN SERIES

TAXONOMIC CLASS: Fine-loamy, mixed, superactive, frigid Calcic Argiudolls

This site is from the corn field. Colors are moist soil unless otherwise stated.

Ap--0 to 10 cm; black (10YR 2/1) loam, very dark gray (10YR 3/1) dry; moderate medium cloddy structure parting to strong fine subangular blocky; friable; few fine and medium roots; abrupt smooth boundary.

A--10 to 18 cm; black (10YR 2/1) loam, very dark gray (10YR 3/1) dry; moderate fine subangular blocky structure; friable; few fine and medium roots; gradual wavy boundary.

Bt1--18 to 33 cm; black (10YR 2/1) and dark brown (10YR 3/3) clay loam; strong medium prismatic structure parting to moderate medium subangular blocky; friable; many faint very dark grayish brown (10YR 3/2) clay films on faces of peds; very few fine and medium roots; gradual smooth boundary.

Bt2--33 to 41 cm; dark brown (10YR 3/3) loam; moderate fine subangular blocky structure; friable; many faint very dark grayish brown (10YR 3/2) clay films on faces of peds; very few fine roots; clear smooth boundary.

Bk--41 to 54 cm; brown (10YR 4/3) loamy sand; weak medium subangular blocky structure; very friable; common medium prominent strong brown (7.5YR 4/6) redoximorphic concentrations; very few fine roots; about 12 percent gravel; violent effervescence; abrupt smooth boundary.

2Btk--54 to 72 cm; light olive brown (2.5Y 5/4) clay loam; moderate medium subangular blocky structure; friable; few fine prominent strong brown (7.5YR 4/6) redoximorphic concentrations; common faint olive brown (2.5Y 4/4) clay films on faces of peds; few fine faint pale yellow (2.5Y 7/3) masses of carbonates; very few fine roots; about 1 percent gravel; violent effervescence; clear smooth boundary.

2Bk1--72 to 90 cm; light olive brown (2.5Y 5/4) clay loam; moderate

Table S2. Continued

medium prismatic structure parting to moderate medium platy; friable; few fine prominent strong brown (7.5YR 4/6) redoximorphic concentrations and many medium distinct light gray (2.5Y 7/1) depletions; very few fine roots; about 1 percent gravel; violent effervescence; clear smooth boundary.

2Bk2--90 to 105 cm; olive brown (2.5Y 4/4) clay loam; weak coarse prismatic structure parting to moderate medium platy; friable; common fine prominent strong brown (7.5YR 4/6) redoximorphic concentrations and many medium prominent gray (5Y 6/1) depletions; few fine prominent black (10YR 2/1) soft masses of iron-manganese; very few very fine roots; about 2 percent gravel; strong effervescence; clear smooth boundary.

2C--105 to 200 cm; light olive brown (2.5Y 5/3) clay loam; massive parting to moderate coarse platy; friable; common fine prominent strong brown (7.5YR 4/6) redoximorphic concentrations and many medium prominent gray (5Y 6/1) depletions; strong effervescence.

**Corsica E,
SD**

Tree windbreak. Described by Steve Winter and Lance Howe

EAKIN SERIES

TAXONOMIC CLASS: Fine-silty, mixed, superactive, mesic Typic Argiustoll

This is a well-drained site with a 0 to 1 percent slope formed in glacial till. Colors are for moist soil unless otherwise stated.

Ap--0 to 20 cm; very dark grayish brown (10YR 3/2) silty clay loam, dark grayish brown (10YR 4/2) dry; weak fine granular structure; few coarse and many medium and fine roots; common very fine pores; abrupt smooth boundary.

Bt--20 to 30 cm; dark grayish brown (10YR 4/2) silty clay loam, brown (10YR 4/3) dry; moderate medium to fine subangular blocky structure; few coarse and many medium and fine roots; few very fine pores; clay films on vertical faces of peds; clear wavy boundary.

Bk1--30 to 62 cm; brown (10YR 4/3) silty clay loam, light olive brown (2.5Y 5/3) dry; weak medium to fine subangular blocky structure; common medium and fine roots; common very fine pores; common fine and medium masses of carbonates; violently effervescent; gradual wavy

Table S2. Continued

boundary.

2Bk2--62 to 97 cm; olive brown (2.5Y 4/4) loam, light olive brown (2.5Y 5/4) dry; weak medium to fine subangular blocky structure; common fine roots; common very fine pores; many fine yellowish brown (10YR 5/6) Fe concentrations; many medium and fine gray (2.5Y 5/1) Fe depletions; many medium and fine masses of carbonates; violently effervescent; gradual wavy boundary.

2C--97 to 150 cm; olive brown (2.5Y 4/3) loam, light olive brown (2.5Y 5/3) dry; massive; few very fine roots; few very fine pores; many medium yellowish brown (10YR 5/6) Fe concentrations; many medium and fine gray (2.5Y 5/1) Fe depletions; some varves in areas; strongly effervescent.

Corsica E,
SD

Hay field. Described by Steve Winter and Lance Howe

EAKIN SERIES

TAXONOMIC CLASS: Fine-silty, mixed, superactive, mesic Typic Argiustoll

This is a well-drained site with a 0 to 1 percent slope formed in glacial till. Colors are for moist soil unless otherwise stated.

Ap--0 to 14 cm; very dark grayish brown (10YR 3/2) silty clay loam, dark grayish brown (10YR 4/2) dry; weak medium to fine granular structure; many medium and fine roots; common very fine pores; abrupt smooth boundary.

Bt--14 to 33 cm; dark grayish brown (10YR 4/2) silty clay loam, brown (10YR 4/3) dry; moderate medium prismatic structure parting to moderate medium to fine subangular blocky structure; common fine roots; few very fine pores; clay films on vertical faces of peds; clear smooth boundary.

Bk1--33 to 54 cm; olive brown (2.5Y 4/3) silty clay loam, light olive brown (2.5Y 5/4) dry; moderate medium to fine subangular blocky structure; common fine and very fine roots; common very fine pores; common fine and medium masses of carbonates; violently effervescent; gradual wavy boundary.

Bk2--54 to 84 cm; olive brown (2.5Y 4/4) silty clay loam, light yellowish brown (2.5Y 6/4) dry; weak medium to fine subangular blocky structure; common fine and very fine roots; common very fine pores; many fine and

Table S2. Continued

medium masses of carbonates; violently effervescent; gradual wavy boundary.

2Bk3--84 to 114 cm; olive brown (2.5Y 4/3) clay loam, light olive brown (2.5Y 5/4) dry; weak medium to fine subangular blocky structure; few very fine roots; common very fine pores; few fine gray (2.5Y 5/1) Fe depletions; many fine and medium masses of carbonates; violently effervescent; clear wavy boundary.

2C--114 to 160 cm; olive brown (2.5Y 4/3) clay loam, light olive brown (2.5Y 5/3) dry; massive; few very fine roots; few very fine pores; common fine yellowish brown (10YR 5/6) Fe concentrations; many medium and fine gray (2.5Y 5/1) Fe depletions; strongly effervescent.

Corsica W,
SD

Tree windbreak. Described by Steve Winter and Lance Howe

MOBRIDGE SERIES

TAXONOMIC CLASS: Fine-silty, mixed, superactive, mesic Pachic Argiustoll

This is a well-drained site with a 0 to 1 percent slope formed in glacial till. Colors are for moist soil unless otherwise stated.

A1--0 to 11 cm; black (10YR 2/1) silt loam, dark gray (10YR 4/1) dry; weak fine subangular blocky structure parting to weak medium to fine granular structure; many medium and fine roots; common very fine pores; clear smooth boundary.

A2--11 to 31 cm; very dark brown (10YR 2/2) silt loam, dark grayish brown (10YR 4/2) dry; weak fine subangular blocky structure parting to weak medium to fine granular structure; many medium and fine roots; common very fine pores; clear smooth boundary.

A3--31 to 47 cm; very dark brown (10YR 2/2) silt loam, dark grayish brown (10YR 4/2) dry; weak fine subangular blocky structure; many medium and fine roots; common very fine pores; clear smooth boundary.

Bt1--47 to 75 cm; very dark grayish brown (10YR 3/2) silty clay loam, brown (10YR 4/3) dry; moderate medium prismatic structure parting to

moderate medium to fine subangular blocky structure; common medium

Table S2. Continued

and fine roots; few very fine pores; clay films on vertical faces of peds; gradual wavy boundary.

Bt2--75 to 116 cm; black (10YR 2/1) silty clay loam, very dark grey (10YR 3/1) dry; moderate medium prismatic structure parting to moderate medium to fine subangular blocky structure; common fine and very fine roots; few very fine pores; clay films on vertical faces of peds; gradual wavy boundary.

Btk--116 to 136 cm; dark olive brown (2.5Y 3/3) silty clay loam, olive brown (2.5Y 4/3) dry; moderate medium prismatic structure parting to moderate medium to fine subangular blocky structure; few fine and very fine roots; common very fine pores; clay films on vertical faces of peds; few fine yellowish brown (10YR 5/6) Fe concentrations; carbonate threads; strongly effervescent; gradual wavy boundary.

Bk--136 to 150 cm; olive brown (2.5Y 4/3) silty clay loam, light olive brown (2.5Y 5/3) dry; weak medium to fine subangular blocky structure; few very fine roots; common fine and very fine pores; common fine yellowish brown (10YR 5/6) Fe concentrations; common fine gray (2.5Y 5/1) Fe depletions; carbonate threads; violently effervescent.

**Corsica W,
SD**

**Pasture. Described by Steve Winter and Lance Howe
EAKIN SERIES**

TAXONOMIC CLASS: Fine-silty, mixed, superactive, mesic Typic Argiustoll

This is a well-drained site with a 0 to 1 percent slope formed in glacial till. Colors are for moist soil unless otherwise stated.

A--0 to 19 cm; very dark brown (10YR 2/2) silty clay loam, dark grayish brown (10YR 4/2) dry; weak fine subangular blocky structure parting to weak medium to fine granular structure; many medium and fine roots; common very fine pores; clear smooth boundary.

Bt--19 to 29 cm; dark brown (10YR 3/3) silty clay loam, brown (10YR 4/3) dry; moderate medium prismatic structure parting to moderate medium to fine subangular blocky structure; common medium and fine roots; common very fine pores; clay films on vertical faces of peds; clear wavy boundary.

Bk1--29 to 43 cm; olive brown (2.5Y 4/3) silty clay loam, light olive

Table S2. Continued

brown (2.5Y 5/3) dry; weak medium to fine subangular blocky structure; common fine and very fine roots; common very fine pores; common fine and medium masses of carbonates; violently effervescent; gradual wavy boundary.

2Bk2--43 to 77 cm; light olive brown (2.5Y 5/3) clay loam, light yellowish brown (2.5Y 6/3) dry; weak medium to fine subangular blocky structure; common fine and very fine roots; common fine and very fine pores; common fine and medium masses of carbonates; violently effervescent; gradual wavy boundary.

2C--77 to 150 cm; light olive brown (2.5Y 5/4) clay loam, light yellowish brown (2.5Y 6/4) dry; massive; few very fine roots; few very fine pores; common fine yellowish brown (10YR 5/6) Fe concentrations; many medium and fine gray (2.5Y 5/1) Fe depletions; strongly effervescent.

Mead, NE

Tree windbreak. Described by C. Latta and B Evans

TOMEK SERIES

TAXONOMIC CLASS: Fine, smectitic, mesic Pachic Argiudoll

This site is on a well-drained loess upland with a udic temperature regime. Colors are for moist soil unless otherwise stated.

Ap--0 to 22 cm; very dark gray (10YR 3/1) silt loam; weak fine granular structure; soft, friable, slightly sticky, slightly plastic; clear smooth boundary.

Bt1--22 to 34 cm; very dark gray (10YR 3/1) silty clay loam; weak medium subangular blocky structure; slightly hard, friable, moderately sticky, moderately plastic; clear smooth boundary.

Bt2--34 to 52 cm; very dark grayish brown (10YR 3/2) silty clay loam; moderate medium to fine subangular blocky structure; slightly hard, firm, moderately sticky, moderately plastic; clear smooth boundary.

Bt3--52 to 80 cm; brown (10YR 4/3) silty clay loam; moderate medium to fine subangular blocky structure; slightly hard, firm, moderately sticky, moderately plastic; clear smooth boundary.

Bt4--80 to 107 cm; brown (10YR 4/3) silty clay loam; weak fine prismatic structure parting to weak fine subangular blocky structure; slightly hard,

Table S2. Continued

firm, moderately sticky, moderately plastic; clear smooth boundary.

BC--107 to 130 cm; brown (10YR 5/3) silt loam; weak fine prismatic structure; slightly hard, friable, moderately sticky, moderately plastic; common medium distinct strong brown (7.5YR 5/6) Fe concentrations; slightly effervescent.

Mead, NE

Row crop field. Described by C. Latta and B Evans

TOMEK SERIES

TAXONOMIC CLASS: Fine, smectitic, mesic Pachic Argiudoll

This site is on a well-drained loess upland with 1 percent slope and a udic temperature regime. Colors are for moist soil unless otherwise stated.

Ap1--0 to 11 cm; very dark grayish brown (10YR 3/2) silt loam; weak medium cloddy structure; soft, very friable, slightly sticky, slightly plastic; abrupt smooth boundary.

Ap2--11 to 23 cm; very dark grayish brown (10YR 3/2) silt loam; weak fine cloddy structure; soft, very friable, slightly sticky, slightly plastic; abrupt smooth boundary.

A--23 to 48 cm; very dark grayish brown (10YR 3/2) silt loam; moderate medium granular structure; soft, very friable, slightly sticky, slightly plastic; clear smooth boundary.

Bt1--48 to 70 cm; very dark grayish brown (10YR 3/2) silty clay loam; moderate fine subangular blocky structure; slightly hard, friable, moderately sticky, moderately plastic; clear smooth boundary.

Bt2--70 to 86 cm; very dark grayish brown (10YR 3/2) silty clay loam; strong fine subangular blocky structure; slightly hard, friable, moderately sticky, moderately plastic; clear smooth boundary

Bt3--86 to 98 cm; very dark grayish brown (10YR 3/2) silty clay loam; strong fine subangular blocky structure; slightly hard, firm, moderately sticky, moderately plastic; few fine distinct dark yellowish brown (10YR 4/6) Fe concentrations; clear smooth boundary.

Bt4--98 to 113 cm; dark grayish brown (10YR 4/2) silty clay loam; strong fine subangular blocky structure; hard, firm, moderately sticky, moderately plastic; common fine distinct dark yellowish brown (10YR 4/6) Fe

Table S2. Continued

concentrations; clear smooth boundary.

Bt5--113 to 150 cm; brown (10YR 4/3) silty clay loam; strong medium subangular blocky structure; hard, firm, moderately sticky, moderately plastic; common fine distinct dark yellowish brown (10YR 4/6) Fe concentrations.

Stromsburg, NE **Tree windbreak. Described by C. Latta and B Evans**

HASTINGS SERIES

TAXONOMIC CLASS: Fine, smectitic, mesic Udic Argiustoll

This site is on a loess upland. Colors are for moist soil unless otherwise stated.

Ap1--0 to 17 cm; very dark grayish brown (10YR 3/2) silt loam; weak fine granular structure; soft, friable, slightly sticky, slightly plastic; abrupt smooth boundary.

Ap2--17 to 32 cm; very dark grayish brown (10YR 3/2) silt loam; weak medium to fine granular structure; soft, friable, slightly sticky, slightly plastic; abrupt smooth boundary.

Bt1--32 to 48 cm; very dark grayish brown (10YR 3/2) silty clay loam; moderate medium to fine subangular blocky structure; slightly hard, firm, moderately sticky, moderately plastic; clear smooth boundary.

Bt2--48 to 66 cm; dark brown (10YR 3/3) silty clay loam; moderate medium to fine prismatic structure parting to moderate medium to fine subangular blocky structure; slightly hard, firm, moderately sticky, moderately plastic; clear smooth boundary.

Bt3--66 to 88 cm; brown (10YR 4/3) silty clay loam; moderate medium prismatic structure parting to moderate medium subangular blocky structure; slightly hard, firm, moderately sticky, moderately plastic; clear smooth boundary.

Bt4--88 to 107 cm; brown (10YR 5/3) silty clay loam; moderate medium prismatic structure parting to moderate medium subangular blocky structure; slightly hard, firm, moderately sticky, moderately plastic; clear smooth boundary.

Table S2. Continued

BC--107 to 148 cm; brown (10YR 5/3) silt loam; weak coarse prismatic structure parting to weak coarse subangular blocky structure; soft, friable, slightly sticky, slightly plastic.

Stromsburg, NE **Alfalfa field. Described by C. Latta and B Evans**

HASTINGS SERIES

TAXONOMIC CLASS: Fine, smectitic, mesic Udic Argiustoll

This site is on a loess upland. Colors are for moist soil unless otherwise stated.

Ap1--0 to 11 cm; very dark grayish brown (10YR 3/2) silt loam; weak fine subangular blocky structure; soft, friable, slightly sticky, slightly plastic; abrupt smooth boundary.

Ap2--11 to 24 cm; very dark grayish brown (10YR 3/2) silt loam; weak fine subangular blocky structure parting to moderate fine platy structure; soft, friable, slightly sticky, slightly plastic; clear smooth boundary.

A--24 to 46 cm; very dark grayish brown (10YR 3/2) silt loam; moderate medium granular structure; soft, friable, slightly sticky, slightly plastic; clear smooth boundary.

Bt1--46 to 68 cm; dark grayish brown (10YR 4/2) silty clay loam; moderate fine subangular blocky structure; slightly hard, firm, moderately sticky, moderately plastic; clear smooth boundary.

Bt2--68 to 98 cm; brown (10YR 5/3) silty clay loam; moderate medium subangular blocky structure; slightly hard, firm, moderately sticky, moderately plastic; clear smooth boundary.

Bt3--98 to 124 cm; brown (10YR 5/3) silty clay loam; weak medium prismatic structure parting to weak medium subangular blocky structure; slightly hard, firm, moderately sticky, moderately plastic; clear smooth boundary.

BC--124 to 156 cm; brown (10YR 5/3) silt loam; weak medium prismatic structure; soft, friable, slightly sticky, slightly plastic; few fine strong brown (7.5YR 5/6) Fe concentrations.

Table S2. Continued

Marquette,
KS

Tree windbreak. described by Tyler Labenz

WELLS SERIES

TAXONOMIC CLASS: Fine-loamy, mixed, active, mesic Udic Argiustoll

Colors are for moist soils unless otherwise stated.

Ap--0 to 13 centimeters; loam, dark brown (7.5YR 3/2), moist; moderate fine subangular blocky structure, and weak fine granular structure; friable; common fine roots throughout and common medium roots throughout and common coarse roots throughout and few very fine roots throughout; few fine tubular and common very fine tubular pores; noneffervescent; ; abrupt smooth boundary.

A--13 to 23 centimeters; loam, dark brown (7.5YR 3/2), moist; moderate fine subangular blocky structure, and weak fine granular structure; friable; common fine roots throughout and common medium roots throughout and common coarse roots throughout and few very fine roots throughout; few fine tubular and common very fine tubular pores; noneffervescent; ; clear smooth boundary.

Bt1--23 to 47 centimeters; clay loam, dark brown (7.5YR 3/3), moist; weak coarse prismatic structure parts to moderate fine subangular blocky structure; firm; common fine roots throughout and common medium roots throughout; few fine tubular and many very fine tubular pores; 60 percent continuous distinct dark brown (7.5YR 3/3), moist, clay films on all faces of peds; noneffervescent; ; clear smooth boundary.

Bt2--47 to 66 centimeters; clay loam, brown (7.5YR 4/3), moist; moderate fine subangular blocky structure, and moderate medium subangular blocky structure; firm; few fine roots throughout and few medium roots throughout; few fine tubular and few very fine tubular pores; 40 percent continuous distinct dark brown (7.5YR 3/3), moist, clay films on all faces of peds; noneffervescent; ; clear smooth boundary.

Bt3--66 to 81 centimeters; sandy clay loam, brown (7.5YR 4/3), moist; moderate fine subangular blocky structure, and moderate medium subangular blocky structure; firm; few fine roots throughout; few fine tubular and few very fine tubular pores; 25 percent discontinuous distinct dark brown (7.5YR 3/2), moist, clay films on all faces of peds; noneffervescent; ; clear smooth boundary.

Table S2. Continued

Bt4--81 to 100 centimeters; sandy clay loam, brown (7.5YR 4/4), moist; moderate medium subangular blocky structure; friable; few fine roots throughout; common fine tubular and common very fine tubular pores; 20 percent discontinuous distinct brown (7.5YR 4/2), moist, clay films on all faces of peds; 2 percent 2- to 10-millimeter mixed rock fragments; noneffervescent; ; clear smooth boundary.

Bt5--100 to 117 centimeters; sandy clay loam, brown (7.5YR 5/4), moist; 24 percent clay; weak medium subangular blocky structure; friable; few fine roots throughout; common fine tubular and common very fine tubular pores; 10 percent patchy distinct clay films on vertical faces of peds; noneffervescent; ; clear smooth boundary.

BC--117 to 150 centimeters; sandy loam, light brown (7.5YR 6/3), moist; weak fine subangular blocky structure; very friable; few fine roots throughout; few fine tubular and common very fine tubular pores; noneffervescent.

**Marquette,
KS**

**Grass site. Described by Tyler Labenz
WELLS SERIES**

TAXONOMIC CLASS: Fine-loamy, mixed, active, mesic Udic Argiustoll

Colors are for moist soils unless otherwise stated.

Ap--0 to 13 centimeters; loam, dark brown (7.5YR 3/3), moist; moderate fine granular structure, and moderate fine subangular blocky structure; friable; common fine roots throughout and common very fine roots throughout; few very fine tubular pores; noneffervescent; ; abrupt smooth boundary.

A--13 to 23 centimeters; loam, dark brown (7.5YR 3/3), moist; moderate fine granular structure, and moderate fine subangular blocky structure; friable; common very fine roots throughout; common very fine tubular pores; noneffervescent; ; clear smooth boundary.

Bt1--23 to 42 centimeters; clay loam, brown (7.5YR 4/3), moist; moderate medium subangular blocky structure, and moderate fine subangular blocky structure; firm; common very fine roots throughout; many very fine tubular pores; 80 percent continuous distinct dark brown (7.5YR 3/3), moist, clay films on all faces of peds; noneffervescent; ; clear smooth boundary.

Bt2--42 to 71 centimeters; clay loam, brown (7.5YR 4/3), moist; moderate

Table S2. Continued

medium subangular blocky structure, and moderate fine subangular blocky structure; firm; common very fine roots throughout; many very fine tubular pores; 40 percent discontinuous distinct dark brown (7.5YR 3/3), moist, clay films on all faces of peds; noneffervescent; ; clear smooth boundary.

Bt3--71 to 90 centimeters; clay loam, brown (7.5YR 4/4), moist; moderate medium subangular blocky structure, and moderate fine subangular blocky structure; firm; common very fine roots throughout; common very fine tubular pores; 15 percent discontinuous distinct brown (7.5YR 4/3), moist, clay films on vertical faces of peds; noneffervescent; ; clear smooth boundary.

Bt4--90 to 110 centimeters; clay loam, brown (7.5YR 4/4), moist; weak medium subangular blocky structure, and moderate fine subangular blocky structure; friable; common very fine roots throughout; common very fine tubular pores; 8 percent discontinuous distinct brown (7.5YR 4/3), moist, clay films on vertical faces of peds; noneffervescent; ; clear smooth boundary.

Bt5--110 to 130 centimeters; clay loam, brown (7.5YR 5/3), moist; weak medium subangular blocky structure, and moderate fine subangular blocky structure; friable; few very fine roots throughout; few very fine tubular pores; 5 percent patchy distinct clay films on vertical faces of peds; noneffervescent; ; clear smooth boundary.

BC--130 to 150 centimeters; sandy clay loam, brown (7.5YR 5/4), moist; weak fine subangular blocky structure; very friable; few very fine roots throughout; few very fine tubular pores; noneffervescent.

McPherson, KS **Windbreak Site; described by Tyler Labenz**
IRWIN SERIES

TAXONOMIC CLASS: Fine, mixed, superactive, mesic Pachic Argiustoll

Colors are for moist soils unless otherwise stated.

A1--0 to 20 centimeters; silty clay loam, black (10YR 2/1), moist; weak medium subangular blocky structure parts to moderate fine granular structure; friable; common fine roots throughout and few medium roots throughout and many very fine roots throughout; common fine tubular and common coarse tubular and common very fine tubular pores; noneffervescent; ; clear smooth boundary.

Table S2. Continued

A2--20 to 38 centimeters; silty clay loam, black (10YR 2/1), moist; moderate
medium subangular blocky structure parts to weak fine subangular blocky structure; firm; common fine roots throughout and few medium roots throughout and many very fine roots throughout; common fine tubular and few coarse tubular and common very fine tubular pores; noneffervescent; ; clear smooth boundary.

Bt1--38 to 56 centimeters; silty clay, very dark gray (10YR 3/1), moist; moderate
coarse subangular blocky structure, and moderate medium subangular blocky structure; very firm; few fine roots throughout and common very fine roots throughout; common fine tubular and common coarse tubular and common very fine tubular pores; 10 percent black (10YR 2/1), moist, organic stains and
35 percent discontinuous distinct clay films on all faces of peds; noneffervescent; ; clear smooth boundary.

Bt2--56 to 79 centimeters; silty clay, very dark grayish brown (10YR 3/2), moist;
weak coarse subangular blocky structure, and moderate medium subangular blocky structure; very firm; few fine roots throughout and common very fine roots throughout; few fine tubular and few very fine tubular pores; 4 percent black (10YR 2/1), moist, organic stains and 25 percent discontinuous distinct clay films on all faces of peds; noneffervescent; ; abrupt smooth boundary.

Btk1--79 to 87 centimeters; silty clay, dark grayish brown (10YR 4/2), moist;
moderate fine subangular blocky structure, and weak medium subangular blocky structure; firm; few fine roots throughout and few very fine roots throughout; few very fine tubular pores; 10 percent patchy distinct clay films on vertical faces of peds; 6 percent medium carbonate masses; noneffervescent; ; clear smooth boundary.

Btk2--87 to 115 centimeters; silty clay, very dark grayish brown (10YR 3/2), moist;
moderate fine subangular blocky structure, and weak medium subangular blocky structure; firm; few very fine roots throughout; few very fine tubular pores; 10 percent patchy distinct clay films on vertical faces of peds; 6 percent medium carbonate masses; noneffervescent.

Table S2. Continued

McPherson, Crop Site; described by Tyler Labenz
KS IRWIN SERIES

TAXONOMIC CLASS: Fine, mixed, superactive, mesic Udic Argiustoll

Colors are for moist soils unless otherwise stated.

Ap--0 to 12 centimeters; silty clay loam, very dark gray (10YR 3/1), moist; weak fine subangular blocky structure; firm; few fine roots throughout and common very fine roots throughout; common fine tubular and few very fine vesicular pores; noneffervescent; ; abrupt smooth boundary.

Bt1--12 to 26 centimeters; silty clay, very dark gray (10YR 3/1), moist; moderate fine subangular blocky structure, and moderate medium subangular blocky structure; very firm; few fine roots throughout and few medium roots throughout and few very fine roots throughout; common fine tubular and few very fine vesicular pores; 10 percent patchy distinct clay films on all faces of peds and 10 percent very dark gray (10YR 3/1), moist, organic stains; noneffervescent; ; clear smooth boundary.

Bt2--26 to 49 centimeters; silty clay, very dark grayish brown (10YR 3/2), moist; moderate fine subangular blocky structure, and moderate medium subangular blocky structure; very firm; few fine roots throughout and few very fine roots throughout; common fine tubular pores; 4 percent very dark gray (10YR 3/1), moist, organic stains and 25 percent discontinuous distinct clay films on all faces of peds; noneffervescent; ; clear smooth boundary.

Btk1--49 to 64 centimeters; silty clay, dark grayish brown (10YR 4/2), moist; moderate fine subangular blocky structure, and moderate medium subangular blocky structure; very firm; few fine roots throughout and few very fine roots throughout; common very fine tubular pores; 4 percent very dark gray (10YR 3/1), moist, organic stains and 35 percent discontinuous distinct clay films on all faces of peds; 4 percent medium carbonate masses; noneffervescent; ; abrupt smooth boundary.

Btk2--64 to 84 centimeters; silty clay loam, very dark grayish brown (10YR 3/2), moist; moderate fine subangular blocky structure, and

Table S2. Continued

moderate medium subangular blocky structure; firm; few fine roots throughout; few very fine tubular pores; 15 percent patchy distinct clay films on vertical faces of peds; 2 percent strong brown (7.5YR 4/6), moist, iron-manganese concretions; 4 percent medium carbonate masses; noneffervescent; ; clear smooth boundary.

Btk3--84 to 107 centimeters; silty clay loam, very dark grayish brown (10YR 3/2), moist; moderate fine subangular blocky structure, and moderate medium subangular blocky structure; firm; few very fine roots throughout; few very fine tubular pores; 10 percent patchy distinct clay films on vertical faces of peds; 2 percent black (10YR 2/1), moist, iron-manganese nodules and 4 percent strong brown (7.5YR 4/6), moist, iron-manganese concretions; 6 percent medium carbonate masses; noneffervescent; ; gradual smooth boundary.

Btk4--107 to 130 centimeters; silty clay loam, very dark grayish brown (10YR 3/2), moist; moderate fine subangular blocky structure, and moderate medium subangular blocky structure; firm; few very fine roots throughout; few very fine tubular pores; 10 percent patchy distinct clay films on vertical faces of peds; 3 percent strong brown (7.5YR 4/6), moist, iron-manganese concretions and 8 percent black (10YR 2/1), moist, iron-manganese nodules; 6 percent medium carbonate masses; noneffervescent.

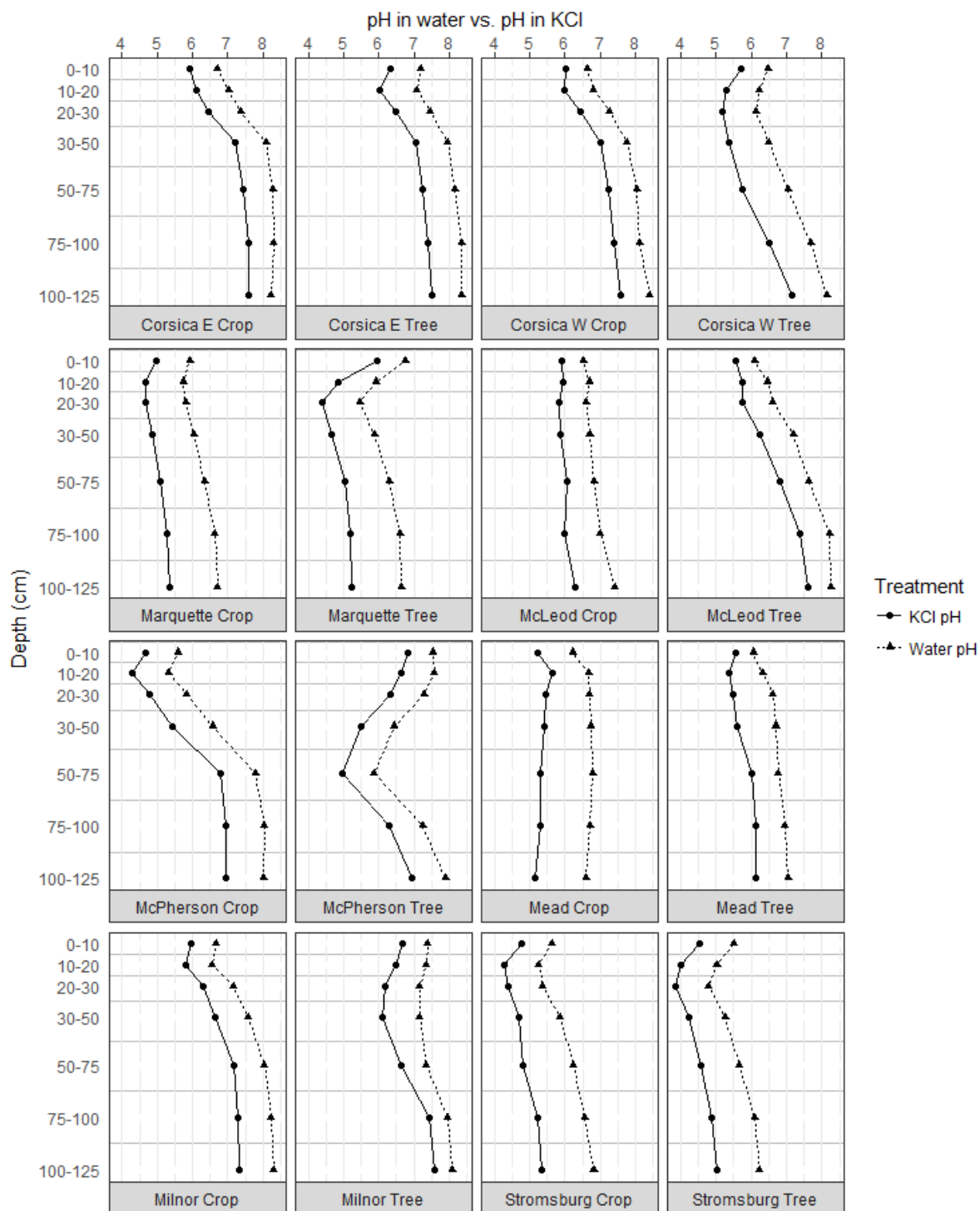


Figure S9. pH in water vs pH in 1MKCl for trees and the adjacent farmed fields for all study sites in the U.S. Great Plains. Crop refers to the adjacent farmed fields.

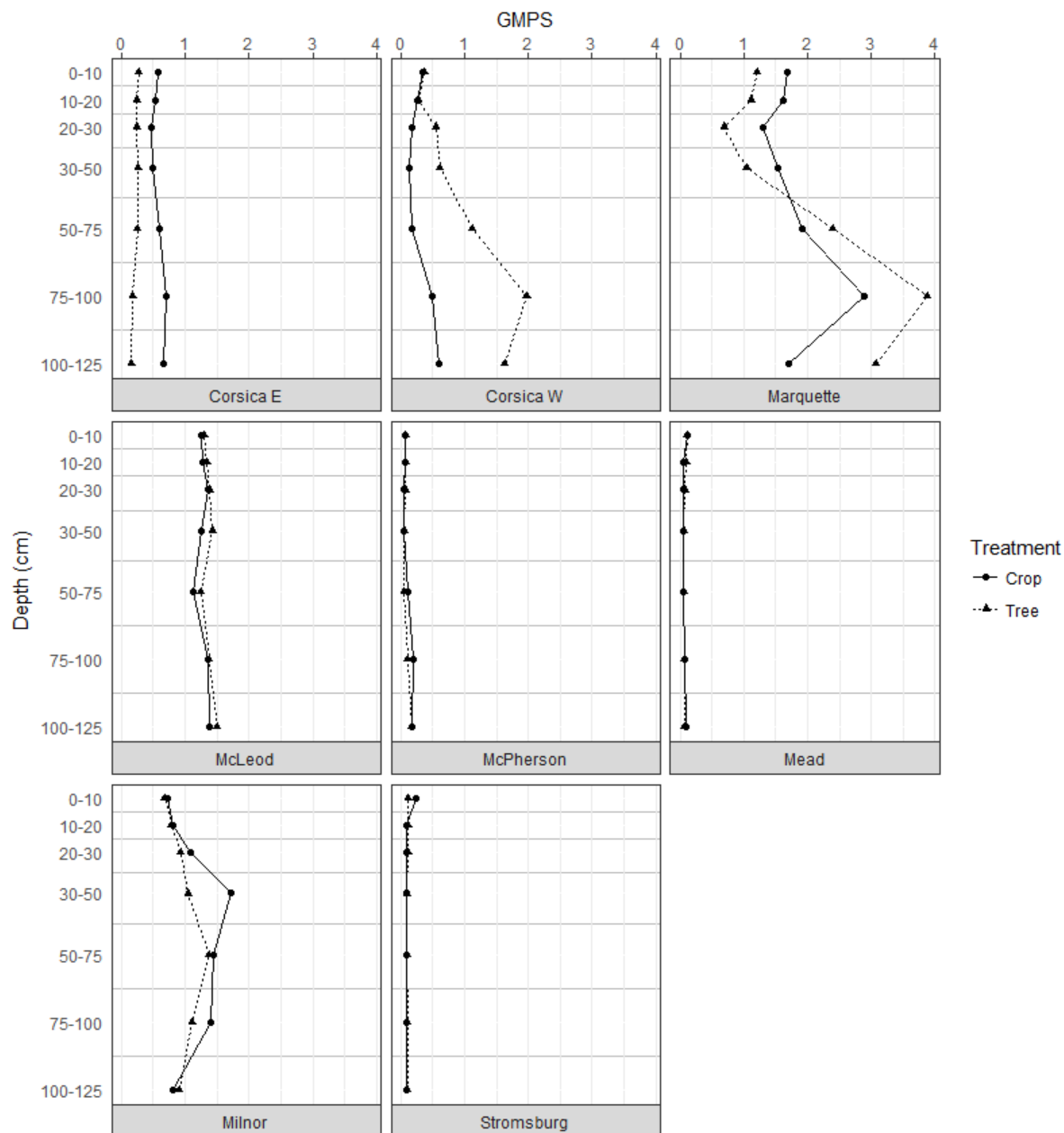


Figure S10. Geometric Mean Particle Size for all study sites.

CHAPTER 3. CONTRIBUTION OF TREE WINDBREAKS TO DEEP SOIL ORGANIC CARBON STORAGE IN SOILS OF THE U.S. GREAT PLAINS.

Modified from a manuscript to be submitted to Global Change Biology

A.A. Khaleel¹, S. J. Hall², M. D. McDaniel³, T. J. Sauer⁴ and J. C. Tyndall¹

Abstract

Agroforestry systems (AFS) (e.g. windbreaks) that integrate trees with agricultural crops or animal production are likely to enhance carbon (C) storage due to deep tree roots. Tree windbreaks are a common agroforestry system practiced historically in the U.S. Northern Great Plains (NGP) after the Dust Bowl of the 1930s to alleviate drought conditions and reduce wind erosion. Earlier studies consistently supported the ability of trees to increase soil organic carbon (SOC) storage relative to treeless systems, however, most of them have been limited to the surface 30 cm of soil. The integration of trees in soils previously managed for crop and/or forage production significantly alters soil properties through fundamental changes in above- and belowground organic inputs, nutrient cycling, and rooting depth and distribution, consequently, affecting C storage and distribution. Studies of source partitioning of SOC under such ecosystems are rare, especially in deep soil depths. To quantify the relative contribution of tree-derived C to total (SOC) in such practice, soil samples were collected at seven depths to 1.25 m within tree plantings and the adjacent farmed fields from eight sites in four Great Plains states (ND, SD, NE, and KS). These sites represent the tree species, soils, previous land use, and climate of the region. The source partitioning of SOC stocks revealed that C₃-derived SOC was higher under trees at nearly all sites and depth

¹ Department of Natural Resource Ecology and Management, Iowa State University, Ames, IA, 50011

² Department of Ecology, Evolution, and Organismal Biology, Iowa State University, Ames, IA, 50011

³ Department of Agronomy, Iowa State University, Ames, IA, 50011

⁴ USDA-ARS, National Laboratory for Agriculture and Environment, Ames, IA, 50011

increments than the adjacent farmed fields. The estimated percentage of C₃-derived SOC beneath trees was higher at the surface and decreased with depth and ranged from 60 to 91% in the surface 0-10 cm. The SOC partitioning data of soils beneath trees and the adjacent farmed fields measured from McLeod, ND, to McPherson, KS, showed a strong north to south decrease in SOC derived from C₃ plants and a corresponding increased contribution from C₄ plants, especially in the subsurface soil. Soils beneath trees averaged $2.93 \pm 2.07 \text{ kg m}^{-2}$ (mean \pm standard error) greater SOC stocks measured to 1.25 m than the adjacent farmed fields. The results indicate that most of the SOC was derived from trees, suggesting that trees have greater potential to store more C in the soil compared with the treeless system.

Nomenclature:

AFS = agroforestry systems

C = carbon

NGP = Northern Great Plains

SOC = soil organic carbon

Keywords: agroforestry, tree windbreaks, Northern Great Plains, soil organic carbon, carbon sequestration, stable carbon isotope.

Introduction

Agroforestry systems (AFS) purposefully integrate trees with agricultural systems to enhance crop productivity and ecosystem functionality at multiple scales (Dosskey *et al.*, 2017). In the United States, AFS have played a significant role in agricultural history. Of singular historical note, initiated by soil erosion conditions in the U.S. Great Plains region that would define the “Dust Bowl” era, the integration of tree-based windbreak systems into row crop dominated landscapes in the 1930s is credited with aiding in that regions soil

erosion recovery (Mason & Karle, 2017). Windbreaks in particular have long been associated with a variety of social, monetary, and environmental benefits in modern agricultural landscapes as well (Brandle *et al.*, 2009). Despite the role that windbreaks can play in agriculture, because of rising land prices, newer cropping technologies that reduce erosion, changes in taxation policies at the state level, and in some cases urban expansion, impetus to maintain or increase tree cover in this region has significantly diminished (Schaefer *et al.*, 1987). Nevertheless, ecosystem benefits from tree-based practices are broadly recognized by landowners in the Great Plains region and these values factor into decisions to integrate trees into their farm systems (Hand *et al.*, 2017). One critical ecosystem benefit associated with windbreaks that resonates with landowners in the region (and globally) is carbon storage particularly in the context of potential carbon markets (Miller *et al.*, 2012; Possu *et al.*, 2016; Hand *et al.*, 2017). A challenge in advancing the C market has been in a need to better understand the mechanisms and processes associated with C storage and dynamics in these ecosystems.

Tree components in AFS can act as a significant sink for atmospheric C due to their long-term storage of significant amount of C in their above- and below-ground biomass (Kort & Turnock, 1999; Kirschbaum, 2003), especially in extensive rooting systems (Haile *et al.*, 2010; Udawatta & Jose, 2011). The integration of trees in AFS can increase C storage potential relative to treeless cropping systems (Jose, 2009). For example, in a Midwestern U.S. study, estimated soil organic carbon (SOC) for the surface 15 cm was significantly greater beneath a 35 yr-old eastern red cedar-Scotch pine windbreak in Nebraska as compared to adjacent cultivated soils (3994 g C m^{-2} vs. 3623 g C m^{-2} , respectively) (Sauer *et al.*, 2007). Similarly, in a study in Northern Italy, Del Galdo *et al.* (2003) found that over a 20

year period, trees planted into cropped soil increased total soil C by 23% and 6% in the 0-10 and the 10-30 cm depth layers, respectively, compared to adjacent cropped soils.

Trees integration on soils previously managed for crop or forage production can significantly alters the quality and quantity of above- and below-ground biomass, rooting distribution and depth, and soil microbial community (Jobbágy & Jackson, 2000; Haile *et al.*, 2008), consequently, affecting SOC abundance and distribution. Trees grown in AFS can affect deep SOC stocks through their extensive deep rooting system (Nair, 2012; Cardinael *et al.*, 2017). The distribution and variation of SOC with depth and beneath trees is still poorly understood. Although the available studies support the expectation that planting trees in and/or around agricultural fields enhance soil C sequestration compared to treeless land-use systems (Hernandez-Ramirez *et al.*, 2011), however, very few studies assessed the impact of trees in AFS on deep SOC (Haile *et al.*, 2010; Cardinael *et al.*, 2015, 2017). Information regarding SOC dynamics and tree influence on C storage in deeper soil layers is still lacking in the literature (Takimoto *et al.*, 2009; Nair, 2012). Perhaps, most of the previous studies of C dynamics in AFS have measured SOC content of the surface 0-30 cm soil depth (Nair, 2012; Cardinael *et al.*, 2015, 2017). Thus, addressing this lack of data on deep SOC in AFS would be an important step towards better understanding of carbon sequestration in AFS in terms of management, modeling and markets (Schoeneberger, 2009; Nair *et al.*, 2010; Capon *et al.*, 2013; Ziegler *et al.*, 2016).

Stable C isotopes are useful for understanding plant-soil SOC dynamics (Ehleringer *et al.*, 2000; Takimoto *et al.*, 2009; Haile *et al.*, 2010; Hernandez-Ramirez *et al.*, 2011). Soils that were initially under C₄ vegetation (e.g., warm-season grasses and crops such as maize *Zea mays*) and then changed to C₃ vegetation (cool-season grasses, forbs, and tree species),

or vice versa, are well suited to study SOC dynamics. The stable C isotope ratio ($^{13}\text{C}/^{12}\text{C}$) expressed as $\delta^{13}\text{C}$ is related to the plants photosynthetic pathway. C_3 and C_4 plants have different photosynthetic pathways that discriminate differently against the naturally occurring ^{13}C isotope. Thus, the C isotope composition of SOM can be used to trace the SOC source (Balesdent and Mariotti 1996; Follet *et al.* 1997; Takimoto *et al.* 2009). The $\delta^{13}\text{C}$ values range of terrestrial plants grown under natural conditions are between -10 and -16‰ for C_4 plants and -22 to -35‰ for C_3 plants (Cerling *et al.*, 1997). Hernandez-Ramirez *et al.* (2011) effectively partitioned the tree-C contribution to SOC and found 53.9 and 47.1% of the SOC in the surface 30 cm soil was tree-derived with mean residence times of 45 and 55 yrs at sites in Nebraska and Iowa, respectively. Similarly, in Northern Italy, Del Galdo *et al.* (2003) used stable C isotopes to study the relative contribution of a 20 yrs old mixed deciduous forest that was planted on soil previously cropped to continuous maize. They found that afforestation resulted in a significant increase in soil C with tree-derived C contributing to 43 and 31% to the total soil C storage in tree soils in the surface 10 and 10-30 cm soil depths.

The change in vegetation after trees integration in AFS on soils previously managed for crop or forage production presents a unique opportunities to use the stable C isotope methodology to study SOC dynamics under such practices. Nonetheless, little information on SOC source partitioning under tree-based systems is currently available, especially at deeper soil depths (Hernandez-Ramirez *et al.*, 2011). With the aim of understanding to what extent trees alter the SOC content and distribution with depth (to 1.25 m) as compared to the adjacent farmed fields. The objective of this study was to quantify the relative contribution of tree-derived C to SOC using the natural C isotopic differences in the Northern US Great Plains.

Materials and Methods

Study sites

This study was conducted within the original Prairie States Forestry Project (PSFP) shelterbelt planting zone (U.S. Forest Service., 1935; Droze, 1977). Site selection was intended to obtain representative soils, tree plantings, and cropping practices for the respective areas. As such, we identified eight sites for soil sampling. Two sites were selected for sampling in each state (North Dakota (ND), South Dakota (SD), Nebraska (NE), and Kansas (KS)). These sites provided a range of climate, soils, tree species, tree age, and cropping practices in adjacent fields. Soil samples were collected from a soil pit and two adjacent auger holes, and soil profile descriptions were prepared for tree plantings and agricultural fields at each site. Detailed climatic and edaphic characteristics of the sites are given in Table 3.1.

Soil sampling

At each site, a soil pit to a depth of ~1.25 m was dug by hand or with a backhoe inside the tree plantings and in the adjacent agricultural lands, which included cultivated fields, alfalfa, grasslands, hay, and pasture. Hereafter, we refer to the adjacent agricultural lands as “adjacent farmed fields”. To enhance our sampling, samples from two hand auger holes adjacent to each pit at each location were also taken. The distance between each auger to the pit was ~ 5 m. Soil samples were collected from 0-10, 10-20, 20-30, 30-50, 50-75, 75-100, and 100-125 cm depth increments within the trees and in the adjacent farmed fields within the same soil map unit for each soil pit and auger holes. Surface litter or crop residue were removed prior to soil sample collection. Soil pit samples were collected from three walls of the soil pit and composited by depth increment. Information and historical records of varying details are available on tree planting and past cropping history at the sites (Table

3.1). In general, the adjacent field at the McLeod (ND) site cultivated began in ~ 1880 and was converted to pasture after the 1935. Similarly, the cultivation of the adjacent small grain field at Milnor site (ND) began in 1880's and continued until 1995 when it was cultivated to corn and soybean rotation. At the Mead site (NE), the adjacent field had been under a crop rotation of corn-soybean-wheat for over 100 years. Likewise, at Stromsburg (NE), the farmed field was mostly been in a wheat-soybean-corn rotation after its first cultivation in the 1890's, but was planted to alfalfa for almost 10 yrs before sampling collection.

Soil preparation and Laboratory Analyses

The field-moist soil samples were passed through an 8-mm sieve and all visible plant material was removed. A subsample of ~200 g of the sieved soil was then passed through a 2-mm sieve. A ~ 20 g sample of air dry < 2-mm-diameter soil was placed on a roller mill (Bailey Mfg., Inc.⁵, Norwalk, IA) for 12 h to create a fine powder consistency.

Organic carbon (OC) and $\delta^{13}\text{C}$ isotopic composition were determined for the whole soil using dry combustion (Flash 1112, Thermo Finnigan, San Jose, CA) interfaced to an isotopic-ratio mass spectrometer (Delta V Advantage, Thermo Fisher Scientific, Waltham, MA). Bulk density was measured following the core method (Soil Survey Laboratory Staff, 1996), core volume 256.35 cm³ (8 cm in diameter and 5.1 cm height), using undisturbed soil samples taken at depths of 0-10, 10-30, 30-75, and 75-100 cm from each of the three pit walls. Cores were weighed, dried at 105°C for 48 hrs and weighed again to determine the oven dry mass.

⁵ Trade names or the commercial products in this article are solely for the purpose of providing specific information and does not imply recommendation or endorsement by authors or their institutions.

Calculation

The C isotope ratios ($\delta^{13}\text{C}$) are reported relative to the Pee Dee Belemnite standard and were calculated as follows (Coplen, 1996):

$$\delta^{13}\text{C} (\text{‰}) = ([R_{\text{sample}} - 1]/R_{\text{standard}}) * 1000 \quad [1]$$

Where;

R_{sample} is the $^{13}\text{C}/^{12}\text{C}$ ratio of the sample.

R_{standard} is the $^{13}\text{C}/^{12}\text{C}$ ratio of the Pee Dee Belemnite standard

The total SOC stocks within the profile were calculated for each soil sample and depth increment as follows (Eq. 2):

$$\text{SOC stocks} = \text{SOC concentration} \times \text{BD} \times \text{Soil layer thickness} \quad [2]$$

Where,

SOC stocks = C stocks expressed in kg m^{-2}

SOC concentration = C in each soil layer, g per kg of soil of that depth

BD = Bulk density, Mg m^{-3}

In ideal terms, using the mass balance equation to estimate fractional tree-derived SOC requires a good representation of the stable C isotope ratios of the soils before tree establishment is needed [i.e. reference site kept under native vegetation]. Thus, using the actual measurements of SOM $\delta^{13}\text{C}$ of afforested soils and actual measured values from reference soil kept under “undisturbed, native prairie vegetation” in the mixing model is preferable. However, if no such reference soil is available, Hernandez-Ramirez *et al.* (2011), used $\delta^{13}\text{C}$ measurements of soil samples taken from the cropped fields adjacent to trees, based on the assumption that these measured $\delta^{13}\text{C}$ values are a good representative of the stable C isotope ratios in the soils before tree plantation, and they successfully quantified the tree contribution to SOC. However, close inspection of the data must be done before.

As described by (Balesdent & Mariotti, 1996) the $\delta^{13}\text{C}$ value of SOC corresponds to C input from the vegetation and thus was used to distinguish the SOC derived from C_3 plants (trees and cool season grasses) and those from C_4 plants (most warm season grasses and corn). Similar to Follett *et al.* (1997), a simple mixing model that assumed average isotope composition for C_3 and C_4 plants to be -26.0 and -12.0‰ , respectively, was used to estimate the relative proportion of SOC derived from C_3 and C_4 plants (Eq. 3 and 4).

$$F_{\text{C3-derived SOC}} = (\delta^{13}\text{C}_{\text{soil sample}} - \delta^{13}\text{C}_{\text{C4}}) / (\delta^{13}\text{C}_{\text{C3}} - \delta^{13}\text{C}_{\text{C4}}) \quad [3]$$

$$F_{\text{C4-derived SOC}} = 1 - F_{\text{C3-derived SOC}} \quad [4]$$

Where;

$F_{\text{C3-derived SOC}}$	= the proportion of SOC derived from C_3 plants
$\delta^{13}\text{C}_{\text{soil sample}}$	= the $\delta^{13}\text{C}$ of SOM of a given soil sample
$\delta^{13}\text{C}_{\text{C3}}$	= the average $\delta^{13}\text{C}$ value of the C_3 plants (-26‰)
$\delta^{13}\text{C}_{\text{C4}}$	= the average $\delta^{13}\text{C}$ value of the C_4 plants (-12‰)
$F_{\text{C4-derived SOC}}$	= the proportion of SOC derived from C_4 plants

Following Haile *et al.* (Haile *et al.*, 2010) the contribution of total SOC by C_3 and C_4 plants were estimated as follows (Eq. 5 and 6) :

$$\text{C}_3\text{-derived SOC} = (F_{\text{C3-derived SOC}}) \times (\text{SOC stocks, kg m}^{-2}) \quad [5]$$

$$\text{C}_4\text{-derived SOC} = (F_{\text{C4-derived SOC}}) \times (\text{SOC stocks, kg m}^{-2}) \quad [6]$$

SOC stocks derived from C_3 or C_4 plants were then added to obtain cumulative C_3 and C_4 -SOC stocks for the 0-30, 30-125, and 0-125 cm soil depths, hereafter we refer to it as “surface soil”, “subsurface soil” and “entire soil profile”, respectively.

Statistical analysis

At each site, a two-sample t-test was used to examine the relative contribution of trees and the adjacent farmed fields to SOC. The differences of C₃- and C₄-derived SOC in the profile was examined as follows; we tested the differences in the surface (0-30cm), subsurface (30-125 cm), and total soil profile (0-125cm). All statistical analyses were performed using R software version 3.4.2 (R Development Core Team, 2013).

Results

Soil C changes

At all sites, SOC concentration decreased with increasing depth (Fig. 3.1). At nearly all sites, the subsurface soils stored more SOC stocks than the surface soils beneath trees (9.54 ± 1.45 vs. 8.84 ± 1.10 kg m⁻²) and beneath the adjacent farmed fields (7.85 ± 1.05 vs. 7.61 ± 0.80 kg m⁻² (mean \pm standard error), respectively (Chapter 2, Table 2.2, and Fig. 2.3). This finding is in general agreement with several previous studies suggesting that deep SOC is a major contributor to the total C pool (Harper & Tibbett, 2013; Cardinael *et al.*, 2015, 2017). Overall, tree soils had higher SOC stocks to 1.25 m and were on average 2.93 ± 2.07 kg m⁻² greater than soils of the adjacent farmed fields.

Soil bulk density at 10 cm was higher by 7.6% in the adjacent farmed fields than the trees (1.42 vs. 1.32 g cm⁻³), respectively, see (Chapter 2, Fig. 2.5). The lower bulk density under trees as compared to the adjacent farmed fields is a common trend and was also observed in other studies (Sauer *et al.*, 2007, 2012; Hernandez-Ramirez *et al.*, 2011).

$\delta^{13}\text{C}$ of SOC and plants

Distinctive soil $\delta^{13}\text{C}$ shifts were detected across all sites and land-use systems (Table 3.2). The $\delta^{13}\text{C}$ values across land-use systems and depth increments varied from -12.83‰ in the adjacent grassland at the Marquette site to much lower values (-24.68‰) beneath the

trees at the McLeod site. Measured $\delta^{13}\text{C}$ values increased with depth at nearly all sites but were not always statistically significant (Table 3.2, Fig. 3.2). Tree soils showed lower $\delta^{13}\text{C}$ values than those for the adjacent farmed fields at nearly all sites and depth increments (Table 3.2). The surface soils beneath trees at the Milnor, Mead, Marquette, and McPherson sites exhibited a pronounced shift in $\delta^{13}\text{C}$ values. The Marquette site had a marked gradient of $\delta^{13}\text{C}$ values, from -15.42‰ under the adjacent farmed field to lower value (-24.15‰) under the trees in the surface 0-10 cm soil. Similar, but less-pronounced trends were observed at the Mead and McPherson sites (Fig. 3.2 e, g, and h). Overall, the mean $\delta^{13}\text{C}$ values of the tree soils ranged from -20.43 to -24.68‰ beneath red cedar trees at Stromsburg site (NE), and ponderosa pine trees at McLeod site (ND), respectively, for the surface 0-10 cm soil depth.

Results from $\delta^{13}\text{C}$ analysis of the soils are consistent with the tree C input being exclusively C_3 while the isotopic values of SOC in adjacent farmed fields are consistent with inputs from a mixture of C_3 and C_4 plants. At some sites, the C_3 plants were more dominant than C_4 , which we attributed to regional vegetation shifts from more C_3 to more C_4 plants from north (e.g. McLeod, ND), to south (e.g. McPherson, KS). This trend may be due to changes in native vegetation with greater dominance of warm season grasses (C_4) at southern sites. This finding is in general agreement with a previous study reporting a regional shift from dominant C_3 to C_4 plants from north to south in the North American Great Plains (Follett *et al.*, 1997). The mean $\delta^{13}\text{C}$ value of above-ground biomass samples averaged -28.23 , -24.08 , and -12.31‰ beneath trees, the adjacent forage lands, and cultivated fields, across all sites respectively.

Plant sources of SOC in soil

On the basis of the mass balance estimation, SOC stocks were separated into those originating from C₃ and C₄ plants. The source partitioning of SOC stocks revealed that C₃-derived SOC was higher under trees at nearly all sites and depth increments than the adjacent farmed fields, except at the Corsica East site (Fig. 3.3). At this site, the soil profile beneath a 15 yrs-old honey locust tree planting had significantly lower SOC stocks compared to the adjacent farmed field (Fig. 3.3c).

Across all sites, SOC stocks derived from C₃ plants were 43, 31, and 37.81% greater under the trees than the adjacent farmed fields (5.67 ± 0.89 vs. 3.95 ± 0.72 , 4.34 ± 0.98 vs. 3.31 ± 0.62 , and 10.01 ± 1.66 vs. 7.26 ± 1.25 kg m⁻² (mean \pm standard error)) in the surface, subsurface, and the entire soil profile, respectively. Overall, soil beneath trees across all sites averaged 2.75 ± 1.10 kg m⁻² (mean \pm standard error) higher C₃ derived SOC stocks than the adjacent farmed fields in the entire soil profile. On average, the differences [between trees and the adjacent farmed fields] in C₃-SOC to 1.25 m ranged from 6.71 under the Osage orange trees at the McPherson site to -3.14 kg m⁻² under honey locust trees at Corsica East site (Table 3.3). Most of the C₃-SOC in the soil profile was found in the surface 0-10 cm layer of soil and was on average 48% greater than the adjacent farmed fields (3.03 ± 0.38 vs. 2.05 ± 0.39 kg m⁻² (mean \pm standard error)). A reverse trend was observed for the SOC derived from C₄ plants, especially in the surface soil, where the adjacent farmed fields across all sites had on average 15% greater C₄-SOC stocks than the tree soils (3.66 vs 3.18 kg m⁻²) (Fig 3.3).

The SOC partitioning data of soils beneath trees and the adjacent farmed fields measured from McLeod, ND, to McPherson, KS, showed a strong north to south decrease in SOC derived from C₃ plants and a corresponding increased contribution from C₄ plants, especially in the subsurface soil of the Mead, Stromsburg, and Marquette sites (Fig 3.3e, f, g,

and h). This finding is similar to the findings of Follett et al. (1997) of regional vegetation patterns of C₃ and C₄ plants.

Discussion

With the objective of assessing the impact of tree plantings on SOC content and distribution, our results showed a consistent pattern of higher SOC stocks beneath trees as compared to the adjacent farmed fields and across all sites. Moreover, the increase in the C₃-derived SOC is consistent with other earlier studies of AFS in the U.S in the surface (Hernandez-Ramirez *et al.*, 2011), and in deeper soil profile (Haile *et al.*, 2008).

The changes in $\delta^{13}\text{C}$ of SOM with depth

The enrichment of SOC $\delta^{13}\text{C}$ with depth is a common trend and was observed in all soils of this study, and soils of other studies examining afforestation of cropped soils effect on SOC (Del Galdo *et al.*, 2003) and in other SOM turnover studies after conversion of forest lands to agricultural lands or vice versa (Balesdent, 1993; Arrouays *et al.*, 1995; Balesdent *et al.*, 1996). The mechanistic basis of SOM $\delta^{13}\text{C}$ enrichment with depth is correlated with the SOM age and degree of decay (Balesdent, 1993; Balesdent & Mariotti, 1996), as well as to the presence of millennia-old C in the profile that is enriched with ^{13}C compared to more recent C (O'Brien and Stout 1978). Further interpretation and explanation on SOM $\delta^{13}\text{C}$ enrichment with depth were given by O'Brien and Stout (1978), Ladyman and Harkness (1980), Balesdent (1993), Bekele and Hudnall (2003), Kramer and Gleixner (2008), and (Ehleringer *et al.*, 2000).

Relative to the adjacent farmed fields, tree soils exhibited lower $\delta^{13}\text{C}$ values in the surface 0-10 cm soil layer (−20.37 vs. −22.78‰), which is attributed to the incorporation of tree litter and biomass to the surface soil after tree establishment, thus indicating a shift in C

source. Similarly, using the natural abundance of C isotopes, both Billings and Richter (2006) and Hernandez-Ramirez et al. (2011) documented lower $\delta^{13}\text{C}$ values under trees when examining the influence of tree development and afforestation of degraded lands on SOM dynamics, respectively.

Tree contribution to SOC with depth.

From this study, it emerged that trees had 16 and 22% greater SOC stocks in the surface and subsurface soils, respectively, as compared to the adjacent farmed fields. The effect of tree planting on SOC storage was observed among all sites, yet the approximate proportion of C_3 and C_4 contributions to SOC varied among sites and depth increments (Fig. 3.3). Some sites had more pronounced changes in the C_3 -SOC than others. For example, at the McPherson site, trees contributed to significantly higher C_3 -SOC stocks as compared to the adjacent farmed field (6.28 vs. 2.76, 5.89 vs. 2.93, and 12.17 vs. 5.69 kg m^{-2}) in the surface, subsurface, and the whole soil profile, respectively (Fig.3.3h and Fig.3.4h). Similarly, C_3 -SOC stocks were higher (but not significantly so) under the trees than in the adjacent farmed field at the Milnor site (Fig. 3.4b). Greater C_3 -SOC was found in the soil profile under the green ash tree plantings as compared to the adjacent farmed field at the Mead site. The adjacent farmed fields at these three sites are in row-crop production and under cultivation, except the McPherson site which has been converted to no till management three years before sampling.

The spatial variation of soil properties at the Mead site may have contributed to anomalous results. At this site, the soil profile description of soil pits under the trees and the adjacent row crop fields showed that the soils were two different series even though the row crop pit was only 20 m from the tree plantings (see: Chapter2. Appendix 1). At the Corsica West site, the surface 10 cm of soil under trees had lower C_3 -SOC stocks than the adjacent

farmed field (Fig. 3.4d). While this site had not been previously tilled, the surface soil under the trees has been disturbed due to cultivation between rows for weed control. In addition, at this particular site, a dense cool season grass canopy (C_3) was found beneath the sparse tree canopy, further complicating the discrimination of C_3 -SOC origin. The relatively low rainfall at Corsica likely resulted in slower tree growth, thus less above- and below-ground tree inputs.

Smaller net changes in C_3 -SOC between trees and the adjacent farmed fields were observed at the McLeod, Stromsburg, and the Marquette sites (Fig. 3.4a, f, and g). C_3 -SOC stocks in the soil profile were 2.32, 1.31, and 2.39 kg m⁻² greater under the trees as compared to the adjacent farmed fields, respectively, and were statistically significant only at Marquette (Table 3.3). At the Marquette site, the field was under cropping management before being simultaneously planted to trees and grassland during the same year.

Belowground biomass is usually an important source of SOC (Takimoto *et al.*, 2009; Haile *et al.*, 2010). Young trees have low organic inputs of tree litter and root biomass during their early years of establishment, hence, may have contributed less to SOC at Stromsburg, Marquette, and Corsica East sites as compared to other sites with older trees. Soil disturbance during tree planting may also be responsible for some of the lower SOC.

However, despite the 80 yr-old ponderosa pine at the McLeod sites, inherent soil properties (e.g. soil texture) also exert a strong influence on SOC storage and turnover. Soil at McLeod is high in sand (91%, see: Chapter 2, Table 2). Sandy soils are known for their low ability to hold nutrients and OM as compared to heavy textured soils, thus a smaller proportion of SOC is likely to be stabilized in soil aggregates as a result of the rapid

decomposition of OM due to the lack of silt and clay contents (Takimoto *et al.*, 2009; Haile *et al.*, 2010).

At the Corsica East, Marquette, and Mead sites, the entire soil profile under the adjacent farmed fields had higher C₄-SOC stocks as compared to the trees but were only significant at Marquette and Mead (Table 3.3). At the Milnor and McPherson sites, unexpectedly higher C₄-SOC stocks under the trees were observed (Fig 3.4b and h). At McPherson at all depths below 10 cm soil under the trees had significantly greater C₄-SOC stocks than the adjacent row crop field (10.78 vs. 6.72 kg m⁻²) (Fig. 3.4h). The lower SOC beneath the adjacent farmed fields as compared to trees could be attributed to soil disturbance through many years of tillage (Fig 3.4b, e, and h). Tillage breaks down soil aggregates and accelerates OM decomposition, thus reduces soil C accumulation. Several studies have shown the beneficial effect of the lack of soil disturbance under trees on SOC storage (West & Post, 2002; Del Galdo *et al.*, 2003; Sauer *et al.*, 2007; Takimoto *et al.*, 2009; Hernandez-Ramirez *et al.*, 2011). For example, Sauer *et al.* (2007) reported greater total SOC stocks in the tree soils of a Nebraska windbreak as a result of lack of tillage beneath the trees. Similarly, Hernandez-Ramirez *et al.* (2011) found that tillage and soil disturbance in the 0-10 cm depth increment of the tilled soils depleted SOC stocks as compared to afforested soils in Iowa and Nebraska.

Other sites showed either net increase or decrease in C₄-SOC stocks under trees. For example, the surface soils under trees at the Corsica West and Stromsburg sites had lower C₄-SOC stocks as compared to the adjacent farmed fields, but, a reverse trend was observed for the subsurface tree soils, where trees had higher C₄-SOC stocks than the adjacent farmed fields. Overall, tree soils across all sites averaged 0.66 and 0.18 kg m⁻² higher C₄-SOC stocks

in the subsurface soil and the entire soil profile, respectively. This finding is contrary to expectations. Normally, a net increase in C₄-SOC in typical soils of C₄ as compared to soils of C₃ vegetation communities (e.g. trees) is more likely to occur.

Conclusion

Our study showed a consistent trend of a shift in SOM $\delta^{13}\text{C}$ values after tree planting. The effect of tree presence on SOC was clear and consistent, the trees could also be expected to contribute to enhanced deep SOC storage in the longer term. Furthermore, the increase in C₃-SOC in this study could be a direct manifestation of the higher tree inputs and slower decomposition rates of C₃-SOC under the trees. The overall results suggest that, in the long-term, tree integration into agricultural systems may help sequester more C in soil and biomass as compared to tree-less system. This long-term C sequestration potential has promising environmental and economic implications. However, more studies on C sequestration potential of trees are still needed, especially in temperate region.

Some limitations, such as the lack of information on belowground biomass turnover (Takimoto *et al.*, 2009; Nair, 2012), and the limited number of studies on deep SOC following tree planted for comparison (Nair, 2012), have contributed to our knowledge gap on C storage and sequestration potential of these ecosystems. Thus, more studies are still needed.

Acknowledgment

The authors sincerely appreciate the field and laboratory assistance of Kevin Jensen, Gavin Simmons, Jody Ohmacht, Amy Morrow, and several student workers at the National Laboratory for Agriculture and the Environment. We are grateful for the cooperation of five

private landowners, staff with the U.S.D.A. Forest Service and Natural Resources Conservation Service, University of Nebraska-Lincoln Eastern Nebraska Research and Extension Center, and soil and water conservation district staff in Polk County, Nebraska and Douglass County, South Dakota. We acknowledge financial support by North Central Sustainable Agriculture Research and Education project LNC12-346.

References

- Arrouays D., Balesdent J., Mariotti A. & Girardin C. (1995). Modeling organic-carbon turnover in cleared temperate forest soils converted to maize cropping by using C-13 natural-abundance measurements. *Plant and Soil*, 173, 191–196.
<https://doi.org/10.1007/bf00011455>.
- Balesdent J. (1993). Site-Related $\delta^{13}\text{C}$ of Tree Leaves and Soil Organic Matter in a Temperate Forest. Author(s): Jérôme Balesdent, Cyril Girardin and André Mariotti. Published by: Wiley on behalf of the Ecological Society of America. Stable URL: [http://www.jstor.org/s. Ecology, 74\(6\), 1713–1721](http://www.jstor.org/s. Ecology, 74(6), 1713–1721).
- Balesdent J. & Mariotti A. (1996). Measurement of soil organic matter turnover using ^{13}C natural abundance. *Mass Spectrometry of Soils; Boutton, T.W., Yamasaki, S., Eds.; New York*, (JANUARY 1996), 47–82.
- Balesdent J., Mariotti A., Boutton T. W. & Yamasaki S. I. (1996). Measurement of soil organic matter turnover using ^{13}C natural abundance. (January 1996), 83–111.
- Bekele A. & Hudnall W. H. (2003). Stable carbon isotope study of the prairie-forest transition soil in Louisiana. *Soil Science*, 168(11), 783–792.
<https://doi.org/10.1097/01.ss.0000100472.96182.d8>.
- Billings S. A. & Richter D. D. (2006). Changes in stable isotopic signatures of soil nitrogen and carbon during 40 years of forest development. *Oecologia*, 148(2), 325–333.
<https://doi.org/10.1007/s00442-006-0366-7>.

Brandle J. R., Hodges L., Tyndall J., Sudmeyer R. A. & Garrett H. E. G. (2009). Windbreak Practices. (1988), 75–104.

<https://doi.org/10.2134/2009.northamericanagroforestry.2ed.c5>.

Capon T., Harris M. & Reeson A. (2013). The Design of Markets for Soil Carbon Sequestration. *Economic Papers: A journal of applied economics and policy*, 32(2), 161–173. <https://doi.org/10.1111/1759-3441.12034>.

Cardinael R., Chevallier T., Barthès B. G., Saby N. P. A., Parent T., Dupraz C., ... Chenu C. (2015). Impact of alley cropping agroforestry on stocks, forms and spatial distribution of soil organic carbon - A case study in a Mediterranean context. *Geoderma*, 259–260, 288–299. <https://doi.org/10.1016/j.geoderma.2015.06.015>.

Cardinael R., Chevallier T., Cambou A., Béral C., Barthès B. G., Dupraz C., ... Chenu C. (2017). Increased soil organic carbon stocks under agroforestry: A survey of six different sites in France. *Agriculture, Ecosystems and Environment*, 236, 243–255. <https://doi.org/10.1016/j.agee.2016.12.011>.

Cerling T. E., Harris J. M., Macfadden B. J., Leakey M. G., Quadek J., Eisenmann V. & Ehleringer J. R. (1997). Global vegetation change through the Miocene / Pliocene boundary. *Nature*, 389, 153–158. <https://doi.org/10.1038/38229>.

Coplen T. B. (1996). Editorial : More uncertainty than necessary the most important recommendation in the are not uniquely defined reported that values (expressed relative to values to hundredths data from marine samples on a per mill because the range of a marine core Appen. *Paleoceanographic Currents*, 11(4), 369–370. <https://doi.org/10.1029/96PA01420>.

Dosskey M. G., Brandle J., Bentrup G., Bell C. A. C., Brantly S., Chambers A., ... Zamora D. (2017). Chapter 2: Reducing threats and enhancing resiliency. In: Schoeneberger, Michele M.; Bentrup, Gary; Patel-Weynand, Toral, eds. 2017. *Agroforestry: Enhancing resiliency in U.S. agricultural landscapes under changing conditions*. Gen. Tech. Report WO-96. Was. 7-42 pp.

- Droze W. H. (1977). *Trees, prairies, and people – a history of tree planting in the Plains States*. Texas Woman's University, Denton.
- Ehleringer J. R., Buchmann N. & Flanagan L. B. (2000). Carbon isotope ratios in belowground carbon cycle processes. *Ecological Applications*, 10(2), 412–422. [https://doi.org/10.1890/1051-0761\(2000\)010\[0412:CIRIBC\]2.0.CO;2](https://doi.org/10.1890/1051-0761(2000)010[0412:CIRIBC]2.0.CO;2).
- Follet R. F., Paul E. A., Leavitt S. W., Halvorson A. D., Lyon D. & Peterson G. A. (1997). *Society of America Journal*, 61, 1068–1077.
- Del Galdo I., Six J., Peressotti A. & Cotrufo M. F. (2003). Assessing the impact of land-use change on soil C sequestration in agricultural soils by means of organic matter fractionation and stable isotopes. *Global Change Biology*, 9, 1204–1213.
- Haile S. G., Nair P. K. R. & Nair V. D. (2008). Carbon Storage of Different Soil-Size Fractions in Florida Silvopastoral Systems. *Journal of Environment Quality*, 37(5), 1789. <https://doi.org/10.2134/jeq2007.0509>.
- Haile S. G., Nair V. D. & Nair P. K. R. (2010). Contribution of trees to carbon storage in soils of silvopastoral systems in Florida, USA. *Global Change Biology*, 16(1), 427–438. <https://doi.org/10.1111/j.1365-2486.2009.01981.x>.
- Hand A. M., Bowman T. & Tyndall J. C. (2017). Influences on farmer and rancher interest in supplying woody biomass for energy in the US Northern Great Plains. *Agroforestry Systems*, 1–14. <https://doi.org/10.1007/s10457-017-0170-x>.
- Harper R. J. & Tibbett M. (2013). The hidden organic carbon in deep mineral soils. *Plant and Soil*, 368(1–2), 641–648. <https://doi.org/10.1007/s11104-013-1600-9>.
- Hernandez-Ramirez G., Sauer T. J., Cambardella C. a., Brandle J. R. & James D. E. (2011). Carbon sources and dynamics in afforested and cultivated Corn Belt soils. *Soil Science Society of America Journal*, 75(1), 216–225. <https://doi.org/10.2136/sssaj2010.0114>.
- Jobbágy E. G. & Jackson R. B. (2000). the Vertical Distribution of Soil Organic Carbon and Its. *Ecological Applications*, 10(2), 423–436. [https://doi.org/10.1890/1051-0761\(2000\)010\[0423:TVDOS0\]2.0.CO;2](https://doi.org/10.1890/1051-0761(2000)010[0423:TVDOS0]2.0.CO;2).

- Jose S. (2009). Agroforestry for ecosystem services and environmental benefits: An overview. *Agroforestry Systems*, 76(1), 1–10. <https://doi.org/10.1007/s10457-009-9229-7>.
- Kirschbaum M. U. F. (2003). Can trees buy time? An assessment of the role of vegetation sinks as part of the global carbon cycle. *Climatic Change*, 58(1–2), 47–71. <https://doi.org/10.1023/A:1023447504860>.
- Kort J. & Turnock R. (1999). Carbon reservoir and biomass in Canadian prairie shelterbelts. *Agroforestry Systems*, 44, 175–186. <https://doi.org/10.1023/A:1006226006785>.
- Kramer C. & Gleixner G. (2008). Soil organic matter in soil depth profiles: Distinct carbon preferences of microbial groups during carbon transformation. *Soil Biology and Biochemistry*, 40(2), 425–433. <https://doi.org/10.1016/j.soilbio.2007.09.016>.
- Ladyman, S.J., Harkness D. D. (1980). Carbon Isotope Measurement As an Index. *Radiocarbon*, 22(3), 885–891.
- Mason A. & Karle S. (2017). *Plains Farms Need Trees*, Vol. 1940. 14-18 pp.
- Miller J. R., Morton L. W., Engle D. M., Debinski D. M. & Harr R. N. (2012). Frontiers in Ecology and the Environment Nature reserves as catalysts for landscape change. *Front Ecol Environ*. <https://doi.org/10.1890/100227>.
- Nair P. K. R. (2012). Carbon sequestration studies in agroforestry systems: A reality-check. *Agroforestry Systems*, 86(2), 243–253. <https://doi.org/10.1007/s10457-011-9434-z>.
- Nair P. K. R., Nair V. D., Kumar B. & Showalter J. M. (2010). Carbon sequestration in agroforestry systems. *Advances in Agronomy*, 108(C), 237–307. [https://doi.org/10.1016/S0065-2113\(10\)08005-3](https://doi.org/10.1016/S0065-2113(10)08005-3).
- O'Brien B. J. & Stout J. D. (1978). Movement and turnover of soil organic matter as indicated by carbon isotope measurements. *Soil Biology and Biochemistry*, 10(4), 309–317. [https://doi.org/10.1016/0038-0717\(78\)90028-7](https://doi.org/10.1016/0038-0717(78)90028-7).

- Possu W. B., Brandle J. R., Domke G. M., Schoeneberger M. & Blankenship E. (2016). Estimating carbon storage in windbreak trees on U.S. agricultural lands. *Agroforestry Systems*, 90(5), 889–904. <https://doi.org/10.1007/s10457-016-9896-0>.
- Sauer T. J., Cambardella C. A. & Brandle J. R. (2007). Soil carbon and tree litter dynamics in a red cedar-scotch pine shelterbelt. *Agroforestry Systems*, 71(3), 163–174. <https://doi.org/10.1007/s10457-007-9072-7>.
- Sauer T. J., James D. E., Cambardella C. A. & Hernandez-Ramirez G. (2012). Soil properties following reforestation or afforestation of marginal cropland. *Plant and Soil*, 360(1–2), 375–390. <https://doi.org/10.1007/s11104-012-1258-8>.
- Schaefer B. P. R., Dronen S. & Erickson D. (1987). Schaefer, P. R., Dronen, S., & Erickson, D. (1987). Windbreaks: a Plains legacy in decline. *Journal of Soil and Water Conservation*, 42(4), 237–238.
- Schoeneberger M. M. (2009). Agroforestry: Working trees for sequestering carbon on agricultural lands. *Agroforestry Systems*, 75(1), 27–37. <https://doi.org/10.1007/s10457-008-9123-8>.
- Takimoto A., Nair V. D. & Nair P. K. R. (2009). Contribution of trees to soil carbon sequestration under agroforestry systems in the West African Sahel. *Agroforestry Systems*, 76(1), 11–25. <https://doi.org/10.1007/s10457-008-9179-5>.
- U.S. Forest Service. (1935). *U.S. Forest Service. 1935. Possibilities of shelterbelt planting in the Plains region. Lake States Forest Experiment Station Special Publication. 201 pp.* 201 pp.
- Udawatta R. P. & Jose S. (2011). Carbon Sequestration Potential of Agroforestry Systems. 8(C). <https://doi.org/10.1007/978-94-007-1630-8>.
- West T. O. & Post W. M. (2002). Soil Organic Carbon Sequestration Rates by Tillage and Crop Rotation : A Global Data Analysis. *Soil Science Society of America Journal*, 66(6), 1930–1946. <https://doi.org/10.2136/sssaj2002.1930>.

Ziegler J., Easter M., Swan A., Brandle J., Ballesteros W., Domke G., ... Paustian K. (2016). A model for estimating windbreak carbon within COMET-FarmTM. *Agroforestry Systems*, 90(5), 875–887. <https://doi.org/10.1007/s10457-016-9977-0>.

Table 3.1. Summary of field locations. Precipitation and temperature data are 30-yr normals from the nearest weather station (National Oceanic and Atmospheric Administration 2002)

Site	MAP (mm)	MAT (°C)	Tree Species & age (years)	Crop (time- years)	Soil (USDA Classification)
McLeod, ND	22.43	43.2	Ponderosa pine (80) <i>Pinus ponderosa</i>	Pasture (80)	Hecla loamy fine sand (Sandy, mixed, frigid Oxyaquic Hapludolls)
Milnor, ND	23.31	43.2	Elm (50+) <i>Ulmus pumila</i>	Row crop (135)	Forman clay loam (Fine- loamy, mixed, superactive, frigid Calcic Argiudolls)
Corsica east, SD	24.94	49.0	Honey locust (15) <i>Gleditsia triacanthos</i>	Hay (15)	Eakin silt loam (Fine-silty, mixed, superactive, mesic Typic Argiustolls)
Corsica west, SD	24.94	49.0	Green ash (25) <i>Fraxinus pennsylvanica</i>	Pasture (125)	Eakin silt loam (Fine-silty, mixed, superactive, mesic Typic Argiustolls)
Mead, NE	29.39	49.9	Green ash ~ (40) <i>Fraxinus pennsylvanica</i>	Row crop (125)	Tomek silt loam (Fine, smectitic, mesic Pachic Argiudolls)
Stromsburg, NE	30.23	50.4	Red cedar (21) <i>Juniperus virginiana</i>	Alfalfa (10)	Hastings silt loam (Fine, smectitic, mesic Udic Argiustolls)
Marquette, KS	32.79	55.1	Black locust (29) <i>Robinia pseudoacacia</i>	Grassland (29)	Irwin loam (Fine, mixed, superactive, mesic Pachic Argiustolls)
McPherson, KS	32.79	55.1	Osage orange (90+) <i>Maclura pomifera</i>	Row crop (115)	Irwin silty clay loam (Fine, mixed, superactive, mesic Pachic Argiustolls)

MAP (Mean Annual Precipitation), MAT (Mean Annual Temperature).

Table 3.2. Mean $\delta^{13}\text{C}$ values of soil organic carbon (SOC) at different depths beneath trees and the adjacent farmed fields in the U.S. Great Plains.

Depth (cm)	$\delta^{13}\text{C}$ values of SOC (‰)							
	McLeod		Milnor		Corsica E		Corsica W	
	Ponderosa pine	Pasture	Elm	Row crop	Honey locust	Hay	Green ash	Pasture
0-10	-24.68	-24.59	-23.78	-21.26	-20.67	-21.58	-21.52	-22.49
10-20	-22.49	-21.69	-22.00	-21.03	-18.75	-19.72	-20.16	-19.29
20-30	-21.18	-19.26	-20.81	-20.91	-18.21	-18.77	-19.77	-18.01
30-50	-19.59	-18.71	-20.89	-21.64	-19.54	-19.19	-18.59	-18.30
50-57	-19.50	-19.09	-21.72	-23.52	-20.94	-21.34	-19.63	-20.22
75-100	-19.24	-18.87	-23.63	-24.46	-21.82	-23.12	-20.13	-21.95
100-125	-19.50	-19.42	-24.39	-25.08	-23.14	-23.82	-20.86	-24.02
	Mead		Stromsburg		Marquette		McPherson	
	Green ash	Row crop	Red cedar	Alfalfa	Black locust	Grassland	Osage orange	Row crop
0-10	-23.47	-18.33	-20.43	-19.14	-24.15	-15.42	-23.55	-20.17
10-20	-19.94	-16.65	-17.71	-16.55	-18.50	-15.33	-20.33	-19.15
20-30	-17.60	-15.76	-15.24	-14.71	-14.26	-13.05	-19.87	-17.48
30-50	-15.72	-14.35	-14.12	-13.71	-13.57	-12.83	-17.88	-17.08
50-57	-16.45	-15.31	-13.81	-14.07	-13.96	-13.59	-17.11	-18.06
75-100	-18.68	-16.47	-15.54	-15.87	-14.66	-13.99	-18.06	-19.03
100-125	-21.77	-17.36	-18.03	-17.82	-16.15	-14.80	-19.46	-18.22

Table 3.2. C₃ and C₄-derived soil organic carbon (SOC) in soils beneath trees and the adjacent farmed fields in the U.S. Great Plains.

	Depth (cm)	McLeod		Milnor		Corsica E		Corsica W	
		Ponderosa pine	Pasture	Elm	Row crop	Honey locust	Hay	Green ash	Pasture
C ₃ -SOC (kg m ⁻²)	0-30	5.54	3.70	10.99	6.91	3.29*	4.84*	6.09	6.60
	30-125	3.15	2.68	6.75	4.12	4.31*	5.9*	9.19**	4.99**
	0-125	8.69	6.38	17.73	11.03	7.56*	10.73*	15.28***	11.58***
C ₄ -SOC (kg m ⁻²)	0-30	1.07	1.22	4.53	3.73	2.86	3.28	3.87	4.05
	30-125	2.77	2.78	2.99	1.09	2.54	2.91	7.47**	3.61**
	0-125	3.87	4.00	7.52	4.82	5.41	6.19	11.34**	7.66**

	Depth (cm)	Mead		Stromsburg		Marquette		McPherson	
		Green ash	Row crop	Red cedar	Alfalfa	Black locust	Alfalfa	Osage orange	Row crop
C ₃ -SOC (kg m ⁻²)	0-30	6.08**	2.89**	3.75	2.85	3.33***	1.07***	6.28*	2.76*
	30-125	2.73*	3.68*	2.03	1.62	0.7	0.57	5.89*	2.93*
	0-125	8.81	6.57	5.78	4.47	4.03**	1.64**	12.17*	5.69*
C ₄ -SOC (kg m ⁻²)	0-30	3.22**	5.09**	4.69	4.86	2.40**	4.30**	2.80	2.71
	30-125	4.92**	10.34**	8.8	7.04	8.8	4.51	7.98***	4.00***
	0-125	8.14**	15.43**	13.49	11.90	6.46*	8.81*	10.78***	6.71***

Means for samples from shelterbelt and the adjacent fields within each depth at each site followed by *, **, or *** indicate significant differences at or < *p* 0.05, 0.01, 0.001 respectively as determined by the Two Sample T test. A simple mixing equation with the average isotope composition ($\delta^{13}\text{C}$) for C₃ and C₄ plants assumed to be -26.0 and -12.0‰.

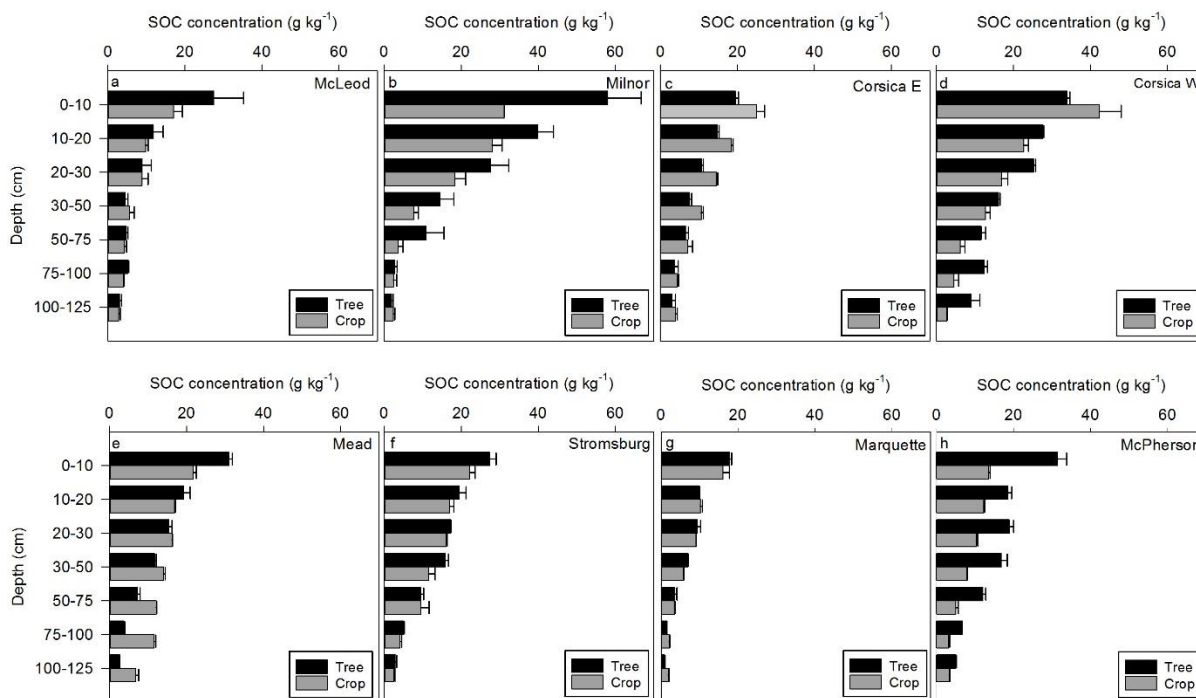


Figure 3.1. Soil organic carbon concentration (g kg^{-1}) with depth for trees and the adjacent farmed fields in the U.S. Great Plains. Error bars represent one standard error of the mean. **a** McLeod, **b** Milnor, **c** Corsica East, **d** Corsica West, **e** Mead, **f** Stromsburg, **g** Marquette, **h** McPherson

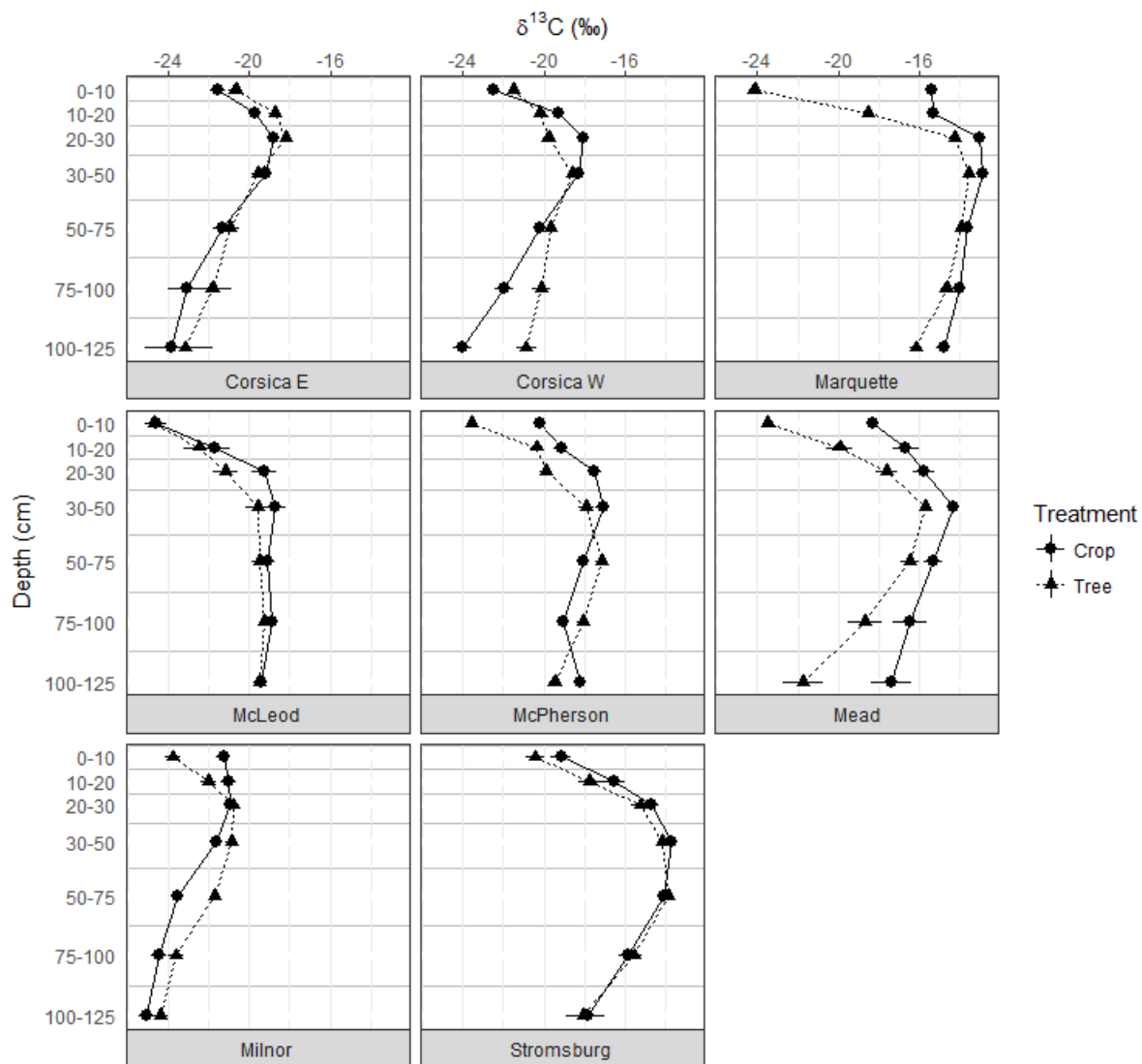


Figure 3.2. Mean $\delta^{13}\text{C}$ values of whole soil for the trees and the adjacent farmed fields in the U.S. Great Plains.

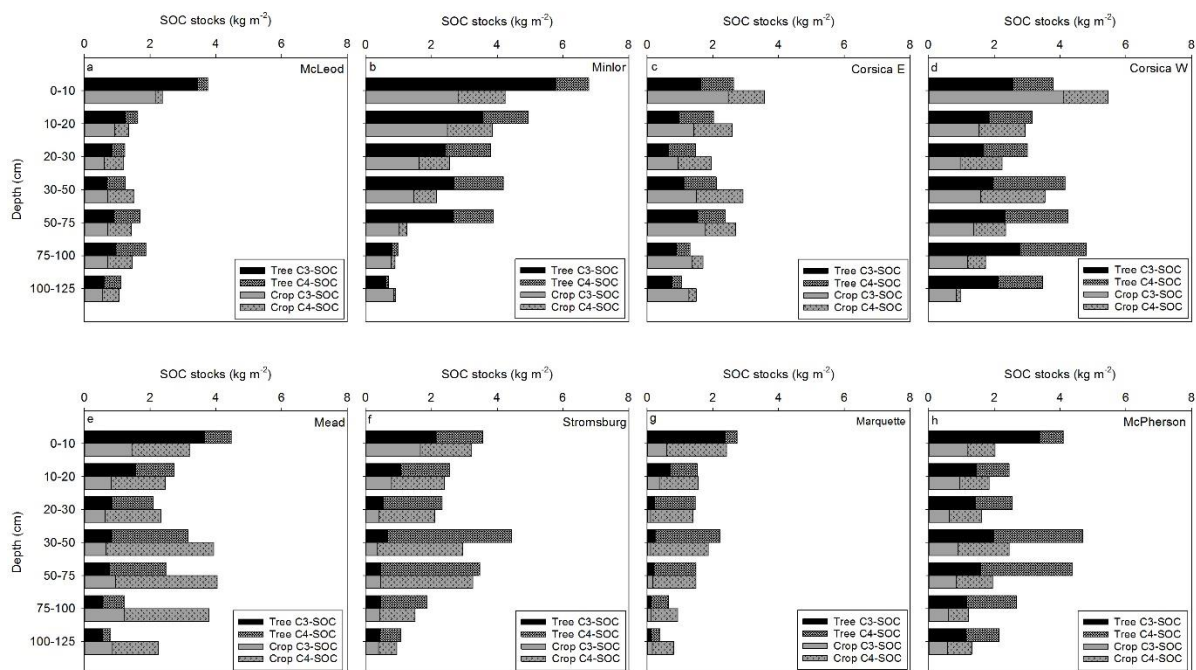


Figure 3.3. Whole SOC stocks divided into C₃ (tree) plant origin and C₄ (warm season grasses) plants origin in different soil depth increments up to 1.25 m in soils of the U.S. Great Plains. **a** McLeod, **b** Milnor, **c** Corsica East, **d** Corsica West, **e** Mead, **f** Stromsburg, **g** Marquette, **h** McPherson.

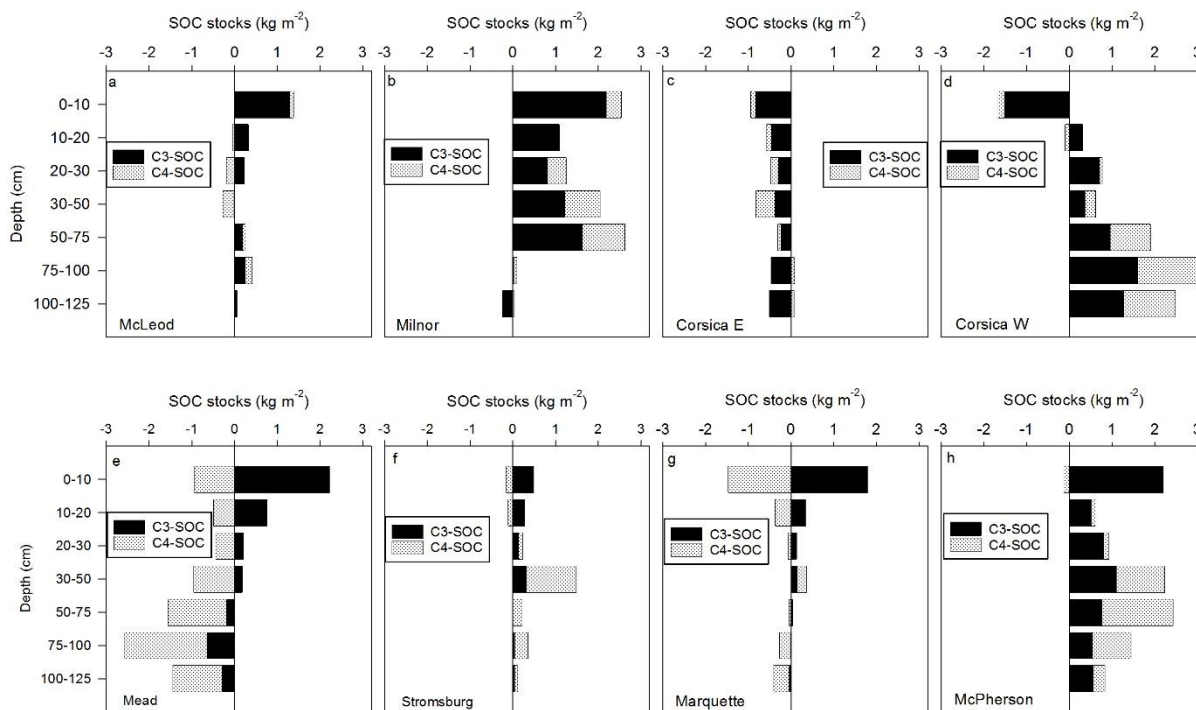


Figure 3.4. Net change of C₃- and C₄-derived SOC stock with depth under tree windbreaks relative to the adjacent farmed fields in the U.S. Great Plains. **a** McLeod, **b** Milnor, **c** Corsica East, **d** Corsica West, **e** Mead, **f** Stombsburg, **g** Marquette, **h** McPherson

CHAPTER 4. CONCLUSION

Climate change will likely to increase drought and wind erosion problems in the Northern Great Plains (NGP) (Joyce et al., 2018). Historically, when similar conditions occurred during the Dust Bowl era of the 1930s, the U.S. Government promoted agroforestry practices to address these environmental problems (Dosskey et al., 2017). Since that time and until the end of 1942, over 220 million trees were planted as windbreaks to improve soil resistance to adverse climatic conditions, improve soil fertility, and to mitigate the effect of the Dust Bowl. The project stretched from North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, and Texas (Droze, 1977; U.S. Forest Service., 1935). After a decade from the project's inception, trees occupied only a small proportion of the landscape, yet their concomitant environmental and economic services were already apparent (Mason & Karle, 2017). Trees have been recognized for their potential to simultaneously help mitigate climate change by sequestering atmospheric carbon (C) in soils and biomass and to stabilize and improve soil fertility, enhancing animal and crop production, while increasing yield and providing other benefits (Brandle, Hodges, Tyndall, Sudmeyer, & Garrett, 2009). The role of trees particularly in the context of agroforestry continues to broadly receive attention as an attractive land use option to help mitigate climate change and improve soil quality (Schoeneberger, 2009). The potential of trees to increase soil organic matter is a critical soil quality features and associated with optimal soil structure, improve infiltration, and soil water storage (Sauer, Cambardella, & Brandle, 2007). Knowledge on the variability of soil C under these systems is important for understanding the impact that tree-based systems may have in enhancing myriad of ecosystem benefits (Dhillon & Van Rees, 2017; Jose & Bardhan, 2012; Lorenz & Lal, 2014; Udawatta, Adhikari, Anoma Senaviratne, & Garrett, 2015).

Nevertheless, in temperate regions (Nair, Nair, Kumar, & Showalter, 2010), quantitative information about belowground C inputs in agroforestry systems continues to be limited (Cardinael et al., 2015; Lorenz & Lal, 2014). Moreover, our understanding of soil organic carbon (SOC) dynamics and storage mechanisms following tree integration into agricultural systems has been limited to the upper 30 cm of surface soil (Haile, Nair, & Nair, 2008; Nair, 2012). Given the paucity of such data especially under temperate agroforestry systems, this study was undertaken to explore the impact that these historical tree plantings in the NGP region have had on SOC storage at deeper depth and their potential to improve overall soil quality on soils in low rainfall areas like the NGP.

To achieve this examination of SOC dynamics, a series of analyses were undertaken utilizing soil samples collected from eight sites in four Northern Great Plains states (two sites in each state, North Dakota, South Dakota, Nebraska, and Kansas), thus capturing a range of climate, soil type, tree species, tree age, and cropping practices in the adjacent fields. The soil samples were taken at seven depths 0-10, 10-20, 20-30, 30-50, 50-75, 75-100, and 100-125 cm within the trees and in the neighboring farmed fields within the same soil map unit.

In the first study (Chapter 2), the results showed that tree soils had on average 1.24, and 1.69 kg m⁻² greater SOC stocks than the adjacent farmed fields, in the surface and the subsurface soil, respectively. The results also revealed that subsurface soils beneath trees and the adjacent farmed fields had greater SOC stocks as compared to surface soil (9.54 vs 8.84 kg m⁻²) and (7.85 vs 7.61 kg m⁻²), respectively. Suggesting that deep SOC is a significant contributor to the C pool as was reported in previous studies (Cardinael et al., 2015; Harper & Tibbett, 2013). Lower bulk density and greater amount of water stable aggregates have been observed under the trees as compared to the adjacent farmed fields.

Stable carbon isotopic ratio study (Chapter 3) showed that tree soils across all sites averaged $2.75 \pm 1.10 \text{ kg m}^{-2}$ (mean \pm standard error) higher C_3 - derived SOC stocks than the adjacent farmed fields in the entire soil profile. The result also revealed that most of the C_3 -SOC in the soil profile was found in the surface 0-10 cm layer of soil and was on average 48% greater than the adjacent farmed fields (3.03 ± 0.38 vs. $2.05 \pm 0.39 \text{ kg m}^{-2}$) (mean \pm standard error).

In conclusion, the two studies included in this thesis sought to advance understanding of the impact of tree plantings on soil organic carbon storage and dynamics, and the relevant soil physical and chemical properties. The results suggest that the higher SOC under trees have occurred primary due to the higher C inputs from above- and belowground biomass and the slower turnover rate of soil organic matter. In addition, overall findings indicated that, trees carbon sequestration potential varies as a result of; site management, lack of tillage, tree age and species, soil texture, and climate. However, current and future C quantity assessments need to be further supplemented with information about the quality and the turnover of the deep SOC. Perhaps, the examination of SOM fractions combined with stable isotope analysis for C source assessment, would provide further insights into SOC dynamics under such practices. In addition, infiltration and soil water holding capacity studies would also further elucidate the benefits of SOC accumulation and storage to the soils and beneath these systems.

References

- Brandle, J. R., Hodges, L., Tyndall, J., Sudmeyer, R. A., & Garrett, H. E. G. (2009). Windbreak Practices, (1988), 75–104.
<https://doi.org/10.2134/2009.northamericanagroforestry.2ed.c5>

- Cardinael, R., Chevallier, T., Barthès, B. G., Saby, N. P. A., Parent, T., Dupraz, C., ... Chenu, C. (2015). Impact of alley cropping agroforestry on stocks, forms and spatial distribution of soil organic carbon - A case study in a Mediterranean context. *Geoderma*, 259–260, 288–299. <https://doi.org/10.1016/j.geoderma.2015.06.015>
- Dhillon, G. S., & Van Rees, K. C. J. (2017). Soil organic carbon sequestration by shelterbelt agroforestry systems in Saskatchewan. *Canadian Journal of Soil Science*, 97(3), 394–409. <https://doi.org/10.1139/cjss-2016-0094>
- Dosskey, M. G., Brandle, J., Bentrup, G., Bell, C. A. C., Brantly, S., Chambers, A., ... Zamora, D. (2017). *Chapter 2: Reducing threats and enhancing resiliency. In: Schoeneberger, Michele M.; Bentrup, Gary; Patel-Weynand, Toral, eds. 2017. Agroforestry: Enhancing resiliency in U.S. agricultural landscapes under changing conditions. Gen. Tech. Report WO-96. Was.*
- Droze, W. H. (1977). *Trees, prairies, and people – a history of tree planting in the Plains States. Texas Woman's University, Denton.No Title.*
- Haile, S. G., Nair, P. K. R., & Nair, V. D. (2008). Carbon Storage of Different Soil-Size Fractions in Florida Silvopastoral Systems. *Journal of Environment Quality*, 37(5), 1789. <https://doi.org/10.2134/jeq2007.0509>
- Harper, R. J., & Tibbett, M. (2013). The hidden organic carbon in deep mineral soils. *Plant and Soil*, 368(1–2), 641–648. <https://doi.org/10.1007/s11104-013-1600-9>
- Jose, S., & Bardhan, S. (2012). Agroforestry for biomass production and carbon sequestration: An overview. *Agroforestry Systems*, 86(2), 105–111. <https://doi.org/10.1007/s10457-012-9573-x>
- Joyce, L. A., Bentrup, G., Cheng, A. S., Kolb, P., Schoeneberger, M., & Derner, J. (2018). Native and agricultural forests at risk to a changing climate in the Northern Plains. *Climatic Change*, 146(1–2), 59–74. <https://doi.org/10.1007/s10584-017-2070-5>
- Lorenz, K., & Lal, R. (2014). Soil organic carbon sequestration in agroforestry systems. A review. *Agronomy for Sustainable Development*, 34(2), 443–454. <https://doi.org/10.1007/s13593-014-0212-y>

- Mason, A., & Karle, S. (2017). *Plains Farms Need Trees* (Vol. 1940).
- Nair, P. K. R. (2012). Carbon sequestration studies in agroforestry systems: A reality-check. *Agroforestry Systems*, 86(2), 243–253. <https://doi.org/10.1007/s10457-011-9434-z>
- Nair, P. K. R., Nair, V. D., Kumar, B., & Showalter, J. M. (2010). Carbon sequestration in agroforestry systems. *Advances in Agronomy*, 108(C), 237–307. [https://doi.org/10.1016/S0065-2113\(10\)08005-3](https://doi.org/10.1016/S0065-2113(10)08005-3)
- Sauer, T. J., Cambardella, C. A., & Brandle, J. R. (2007). Soil carbon and tree litter dynamics in a red cedar-scotch pine shelterbelt. *Agroforestry Systems*, 71(3), 163–174. <https://doi.org/10.1007/s10457-007-9072-7>
- Schoeneberger, M. M. (2009). Agroforestry: Working trees for sequestering carbon on agricultural lands. *Agroforestry Systems*, 75(1), 27–37. <https://doi.org/10.1007/s10457-008-9123-8>
- U.S. Forest Service. (1935). *U.S. Forest Service. 1935. Possibilities of shelterbelt planting in the Plains region. Lake States Forest Experiment Station Special Publication. 201 pp.*
- Udawatta, R. P., Adhikari, P., Anoma Senaviratne, G. M. M. M., & Garrett, H. E. (2015). Variability of soil carbon in row crop watersheds with agroforestry buffers. *Agroforestry Systems*, 89(1), 37–47. <https://doi.org/10.1007/s10457-014-9740-3>